Assessment of the Worldwide Market Potential for Oxidizing Coal Mine Ventilation Air Methane

United States Environmental Protection Agency
Air and Radiation (6202-J)
EPA 430-R-03-002
July 2003

COALBED METHANE OUTREACH PROGRAM

The Coalbed Methane Outreach Program (CMOP) is a part of the US Environmental Protection Agency's (USEPA) Climate Protection Partnerships Division. CMOP is a voluntary program that works with coal companies and related industries to identify technologies, markets, and means of financing the profitable recovery and use of coal mine methane (a greenhouse gas) that would otherwise be vented to the atmosphere.

CMOP assists the coal industry by profiling coal mine methane project opportunities, conducting mine-specific technical and economic assessments, and identifying private, state, local, and federal institutions and programs that could catalyze project development.

United States Environmental Protection Agency

EPA

Assessment of the Worldwide Market Potential for Oxidizing Coal Mine Ventilation Air Methane

July 2003

ACKNOWLEDGMENTS

This report was prepared under USEPA Contract 68-W-00-093 by International Resources Group. The principal authors were H. Lee Schultz, Peter Carothers, Robert Watts, and Robyn McGuckin. The authors and USEPA gratefully acknowledge the vision and direction provided by Karl H. Schultz, Team Leader, Coalbed Methane Program, in planning and overseeing the scope and focus of this assessment. In addition, industry experts from coal-producing countries around the world also provided comments and suggestions that significantly advanced this analysis. Specifically, we wish to recognize the assistance of the following individuals who (a) contributed data for the technology characterization and the country analyses and/or (b) served as peer reviewers of the draft report:

- Zhu Chao (a), Project Manager, China Coalbed Methane Clearinghouse, Beijing, China
- Alexander Filippov (a, b), Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine
- Dr. Jiri Gavor (a, b), Partner, ENA Ltd., Prague, Czech Republic
- Brian King (a, b), Senior Consultant, Neill and Gunter (Nova Scotia) Ltd., Dartmouth, Nova Scotia, Canada
- Jan Kwarcinski (a), Polish Geological Institute, Upper Silesian Branch, Sosnowiec, Poland
- Philip J.D. Lloyd (a), Energy Research Institute, University of Cape Town, South Africa
- Professor Emeritus Jan Mutmansky (a, b), Pennsylvania State University, State College, Pennsylvania, United States
- Vijay Nundlall (a), Inspector of Mines, Occupational Hygiene, Pretoria, South Africa
- Peter Radgen (a, b), Project Manager, Fraunhofer ISI, Karlsruhe, Germany
- Joanne Reilly (b), Senior Geologist, RAG American Holding, Inc., Waynesburg, Pennsylvania, United States

- Patrick Reinks (b), Ingersoll-Rand Company - Energy Systems, Davidson, North Carolina, United States
- Dr. Geoff Rigby (b), Reninna Consulting, New South Wales, Australia
- Abouna Saghafi (b), Principal Research Scientist, CSIRO Exploration and Mining, Sydney, Australia
- Mario Alberto Santillan-Gonzalez (a, b), Mining Engineer, Minerales Monclova S.A. de C.V., Coahuila, Mexico
- Igor A. Shvetz (a), Director, Ispat Karmet JSC, Karaganda, Kazakhstan
- Umesh Prasad Singh (a, b), Deputy Chief Engineer, Coal India, Ltd., Calcutta, India
- Shi Su (b), CSIRO Exploration and Mining, Kenmore, Queensland, Australia
- Dr. Oleg Tailakov (a, b), Director, Russia Coalbed Methane Center, Kemerovo, Russia
- Jerry Triplett (b), Partnership for Energy and Environmental Reform (PEER), Kiev, Ukraine
- Liu Wenge (a, b), Project Manager, China Coalbed Methane Clearinghouse, Beijing, China
- Richard Winschel (b), CONSOL Energy, South Park, Pennsylvania, United States
- Ken Zak (a, b), MEGTEC Systems, DePere, Wisconsin, United States

CONTENTS

Acknowledgments v

Glossary xi

Acronyms xiii

1. Introduction 1

2. Emissions 3
   - 2.1 Methane 3
   - 2.2 Coal Mine Methane 3
   - 2.3 Components and Qualities of CMM 3
   - 2.4 Baseline Emissions Estimation Methodology 4
   - 2.5 Country-Specific Baseline VAM Emission Estimates 6
   - 2.6 Uncertainty in the Baseline Emission Estimates 7
   - 2.7 Emissions Projection Methodology 8
   - 2.8 VAM Emissions Projections 9
   - 2.9 VAM Emissions Projection Uncertainty 9

3. Emission Reductions 11
   - 3.1 Technology Overview 11
     - 3.1.1 Thermal Flow-Reversal Reactor 11
     - 3.1.2 Catalytic Flow-Reversal Reactor 12
     - 3.1.3 Energy Conversion from a Flow-Reversal Reactor 13
     - 3.1.4 Other Technologies 13
   - 3.2 Cost Analysis 17
     - 3.2.1 Methodology 19
     - 3.2.2 Analysis of the MAC Curves 26
     - 3.2.3 Opportunity Cost of VAM Recovery and Use 29
     - 3.2.4 VAM Carbon Mitigation Cost in the Absence of Power Generation 30
     - 3.2.5 Uncertainties 30
     - 3.2.6 Estimating the Effects of Uncertainties on the MAC Curves ... 37
     - 3.2.7 Worldwide Market Potential 38

4. Summary and Conclusions 39

5. References 41

Appendix A. Country-Specific Analyses (2000–2020) 43

VAM Oxidation Market Potential: China 49
VAM Oxidation Market Potential: United States 53
VAM Oxidation Market Potential: Ukraine 57

VAM Oxidation Market Potential: Australia 61
VAM Oxidation Market Potential: Russia 65
VAM Oxidation Market Potential: South Africa 71
VAM Oxidation Market Potential: Poland 73
VAM Oxidation Market Potential: Kazakhstan 77
VAM Oxidation Market Potential: India 81
VAM Oxidation Market Potential: United Kingdom 83
VAM Oxidation Market Potential: Mexico 87
VAM Oxidation Market Potential: Germany 91
VAM Oxidation Market Potential: Czech Republic 95

Appendix B. Sample Calculations 99

Appendix C. Basis for Power Price Used in the Analyses 105

Appendix D. Technology Developer/Vendor Contact Information 109

Appendix E. CMOP Contact Information 113

Tables

Table 1. Countries Analyzed and 2000 VAM Emissions 7
Table 2. Projected Annual VAM Liberation by Country, 2000–2020 10
Table 3. Potential Worldwide Market for VAM Projects 38
Table A. Summary of VAM Liberation Projections, 2000–2020 47

Figures

Figure 1. Contribution of Anthropogenic Emissions of All Greenhouse Gases to the Enhanced Greenhouse Effect Since Industrial Times 3
Figure 2. US Anthropogenic Methane Emissions 3
Figure 3. US Underground CMM Liberation by Source, 2000 4
Figure 4. Illustrative Ventilation Airflow and VAM Concentration Variations 5
Figure 5. Thermal Flow-Reversal Reactor 12
Figure 6. Environmental C & C's Fluidized Bed Concentrator 14
Figure 7. EDL Carbureted Gas Turbine Installation 15
Figure 8. MAC Analysis for the United States—Carbon Mitigation 27
Figure 9. MAC Analysis for the United States—Power Production 27
Figure 10. Global MAC Analysis—Carbon Mitigation 28
Figure 11. Global MAC Analysis—Power Production 28

Figure 12. Global Opportunity Cost Curve 29
Figure 13. US Carbon Mitigation Cost in the Absence of Power Generation 30
Figure A-1. MAC Analysis for China—Power Production 50
Figure A-2. MAC Analysis for China—Carbon Mitigation 51
Figure A-3. Opportunity Costs for China 51
Figure A-4. MAC Analysis for the United States—Power Production 54
Figure A-5. MAC Analysis for the United States—Carbon Mitigation 54
Figure A-6. Opportunity Costs for the United States 55
Figure A-7. MAC Analysis for Ukraine—Power Production 58
Figure A-8. MAC Analysis for Ukraine—Carbon Mitigation 59
Figure A-9. Opportunity Costs for Ukraine 59
Figure A-10. MAC Analysis for Australia—Power Production 62
Figure A-11. MAC Analysis for Australia—Carbon Mitigation 62
Figure A-12. Opportunity Costs for Australia 63
Figure A-13. MAC Analysis for Russia—Power Production 66
Figure A-14. MAC Analysis for Russia—Carbon Mitigation 67
Figure A-15. Opportunity Costs for Russia 68
Figure A-16. MAC Analysis for Poland—Power Production 74
Figure A-17. MAC Analysis for Poland—Carbon Mitigation 74
Figure A-18. Opportunity Costs for Poland 75
Figure A-19. MAC Analysis for Kazakhstan—Power Production 78
Figure A-20. MAC Analysis for Kazakhstan—Carbon Mitigation 78
Figure A-21. Opportunity Costs for Kazakhstan 79
Figure A-22. MAC Analysis for the United Kingdom—Power Production 84
Figure A-23. MAC Analysis for the United Kingdom—Carbon Mitigation 84
Figure A-24. Opportunity Costs for the United Kingdom 85
Figure A-25. MAC Analysis for Mexico—Power Production 88
Figure A-26. MAC Analysis for Mexico—Carbon Mitigation 88
Figure A-27. Opportunity Costs for Mexico 89
Figure A-28. MAC Analysis for Germany—Power Production 92
Figure A-29. MAC Analysis for Germany—Carbon Mitigation 92
Figure A-30. Opportunity Costs for Germany 93
Figure A-31. MAC Analysis for the Czech Republic—Power Production 96
Figure A-32. MAC Analysis for the Czech Republic—Carbon Mitigation 96
Figure A-33. Opportunity Costs for the Czech Republic 97

GLOSSARY

Anthropogenic	Of, relating to, or resulting from human influences on natural systems.
Bleeder shaft	Smaller in diameter than main mine ventilation shafts, used at some mines to increase ventilation at individual or groups of longwall panels.
CH_4	Methane, a greenhouse gas with a 100-year atmospheric forcing factor approximately 21 times that of CO_2.
CO_2	Carbon dioxide, the reference greenhouse gas with a global warming potential of 1.
Gob	Superjacent rock (and coal) strata that fracture and cave into the mining void following coal extraction as the longwall face and hydraulic roof supports advance (termed goaf outside of the United States).
Gob gas	Methane that is released into the gob during and subsequent to gob formation.
Greenhouse gas	Any of a number of gases that trap heat in the Earth's atmosphere, including water vapor, CO_2, CH_4, nitrous oxide, ozone, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).
Tonne	Metric ton (1000 kilograms).
VAM	Ventilation air methane; the methane contained in ventilation airflows exiting gassy underground coal mines.

Acronyms

Bm^3	Billion cubic meters
Btu	British thermal unit
CBM	Coalbed methane
CFRR	Catalytic flow-reversal reactor
CGT	Carbureted gas turbine
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CO_2e	Carbon dioxide equivalent
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
kWh	KiloWatt-hour
MAC	Marginal abatement cost
MBtu	Million British thermal units
Mm^3	Million cubic meters
MMT	Million metric tons (million tonnes)
MW	MegaWatt (million Watts)
MSHA	Mine Safety and Health Administration
NPV	Net present value
TFRR	Thermal flow-reversal reactor
UG	Underground (coal production)

USEPA	United States Environmental Protection Agency
VAM	Ventilation air methane
VOC	Volatile organic compound

1. INTRODUCTION

Methane vented from coal mine exhaust shafts constitutes an unused source of energy and a potent atmospheric greenhouse gas (GHG). Technologies that can reduce ventilation air methane (VAM) emissions while harnessing methane's energy offer significant benefits to the world community. Thermal and catalytic oxidation technologies are both candidates for utilizing the low methane concentrations contained in VAM streams. This report estimates global VAM emissions and the potential for their mitigation.

This assessment focuses on the major coal-producing countries worldwide. Based on 2000 data quantifying country-specific methane emissions from underground coal mining, the countries analyzed comprise an estimated 85 percent of global emissions.

Information provided by volatile organic compound (VOC) oxidation equipment suppliers reveals that technology can oxidize VAM concentrations down to a practical limit of 0.15 percent methane in air and can reliably oxidize and produce energy from VAM concentrations down to 0.2 percent. Because such equipment is employed at industrial installations around the world for VOC emission control, a sound database of oxidizer equipment capital and operating costs is available. Similar data for other system components, such as heat recovery and energy production units, are based on less definitive information.

Using data obtained from both public and private sources, this US Environmental Protection Agency (USEPA) assessment estimates current and projected underground coal production, ventilation airflows, and unitized VAM emission values (i.e., specific emissions). Using those estimates in combination with equipment cost data enabled the development of marginal abatement cost (MAC) curves that illustrate, for each study country and the world overall, the costs associated with mitigating various levels of VAM emission.

2. EMISSIONS

2.1 Methane

The Intergovernmental Panel on Climate Change (IPCC) estimates that methane (CH_4) is 21 times more potent than carbon dioxide (CO_2) over a 100-year timeframe in trapping heat in the atmosphere.[1] It is second only to CO_2 as a contributor to global warming, as shown in Figure 1.[2]

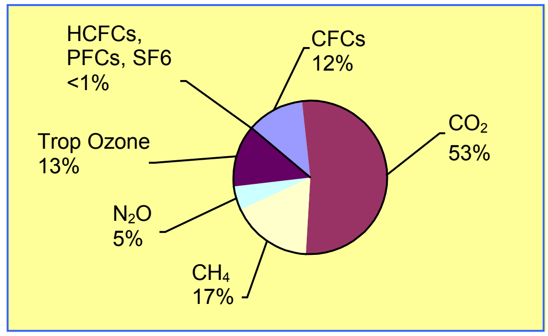

Figure 1. Contribution of Anthropogenic Emissions of All Greenhouse Gases to the Enhanced Greenhouse Effect since Industrial Times (measured in Watts/m^2)

2.2 Coal Mine Methane

Coalbed methane (CBM) is formed during the coalification process and is contained in coal seams and adjacent rock strata. Unless it is intentionally drained from the coal and rock, the process of coal extraction will liberate CBM into the mine workings where it is referred to as coal mine methane (CMM). CMM poses a serious hazard to workers, and mine operators employ large-scale ventilation systems to remove CMM from mine workings. Figure 2 reveals that in the US methane released to the atmosphere from coal mines represents almost 10 percent of the country's anthropogenic methane emissions.[3] Ventilation systems at underground mines account for the bulk of those emissions.

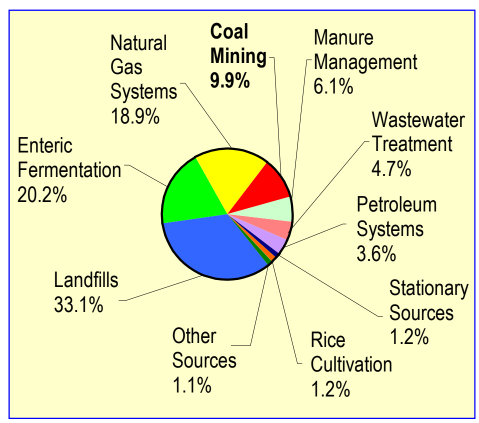

Figure 2. US Anthropogenic Methane Emissions

2.3 Components and Qualities of CMM

Methane emissions to the atmosphere can result from surface mining as overburden is removed and coal is extracted, underground mining as coal is removed and gob

---

[1] This report uses the global warming potentials from the IPCC's Second Assessment Report because these values are used in emissions reporting under the United Nations Framework Convention on Climate Change. The IPCC updated these values in the Third Assessment Report and the relative impact of methane as compared to carbon dioxide increased to 23.

[2] IPCC (2001).

[3] USEPA (2002a).

is formed, and post-mining activities such as coal storage and transportation. USEPA (2002a) reports that in the US in 2000, approximately 65 percent of methane emitted from coal mining came from underground mines, 14 percent from surface mines, and 21 percent from post-mining activities.

Methane liberated by underground coal mining can vary in quality depending on where and how it is liberated. Because there are fewer opportunities for air to dilute it, CBM drained from coal seams in advance of mining is of very high concentration, often meeting natural gas pipeline quality specifications. CMM released from coal and rock strata as gob forms during longwall mining operations (gob gas) unavoidably mixes with mine air thus reducing its concentration. Gob gas generally is considered to be of medium quality (approximately 30–90 percent methane and containing contaminants such as nitrogen, oxygen, carbon dioxide, and water vapor). CMM released to the atmosphere by the mine ventilation system is the lowest concentration, typically below 1 percent.

Figure 3 illustrates the relative magnitude of methane emissions to the atmosphere in the US from mine ventilation and methane drainage systems.[4] As the figure reveals, 27 percent of methane from underground coal mines is drained and used, 7 percent is drained but released to the atmosphere, and 66 percent escapes to the atmosphere through ventilation systems.

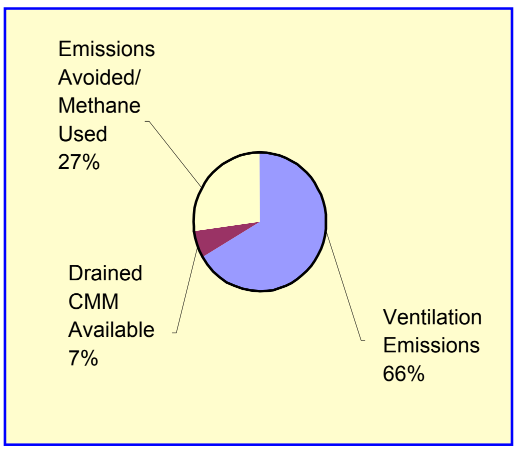

Figure 3. US Underground CMM Liberation by Source, 2000

2.4 Baseline Emissions Estimation Methodology

This section describes the general analytical methodology applied to estimate and project VAM emissions. Appendix A explains the application of this methodology to each country in the analysis.

Variations in ventilation air methane flow and concentration affect the size (ventilation air-processing capacity) and cost of an oxidation system emplacement. For example, Figure 4 provides a graph of such variation over time at an underground coal mine bleeder shaft in the eastern United States.[5] As the figure illustrates, over a 2.25-year period ventilation airflow at this

[4] USEPA (2002b).

[5] Data obtained from the US Mine Safety and Health Administration.

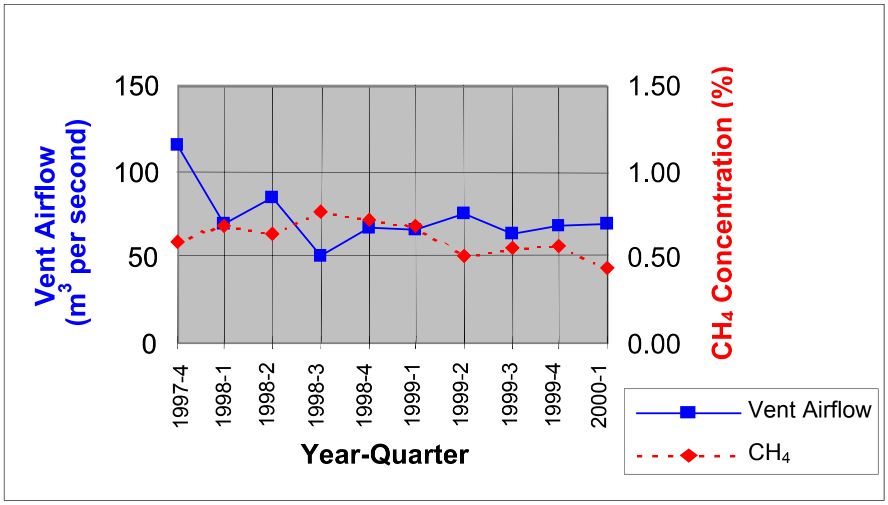

Figure 4. Illustrative Ventilation Airflow and VAM Concentration Variations

shaft ranged from just over 50 to almost 120 m^3 per second and VAM concentration ranged from less than 0.5 to over 0.7 percent.

To account for such variations, the first step in evaluating the potential world market for VAM oxidation equipment involved characterizing VAM flows in major coal-producing countries. To develop a ventilation air emissions baseline, USEPA sought to compile up-to-date, detailed data for the year 2000 for each study country. Rather than relying on emissions factors or other generalized approaches to estimate emissions, when possible USEPA employed the following "bottom up" analytical approach to characterize methane emissions at the shaft level in terms of ventilation airflow rates and VAM concentrations:

1. For each study country, typical ventilation shaft airflows were quantified and both a flow range and a typical value[6] were defined.

2. VAM concentrations also were quantified for each country and both a concentration range and a typical value were defined.

Additionally, total VAM emissions for 2000 were tabulated for each country. The combination of VAM characterization data and VAM emissions for 2000 constituted the study baseline for each country under evaluation.

[6] While conceptually simple, the variation in the type and level of detail of the data available from country to country often made the country-specific VAM characterization challenging. For example, not all countries provided both ventilation airflow and VAM concentration data. For countries that did provide such data, some provided a range as well as a point value (variously reported as average, weighted average, typical, mean, or median), while others provided either a range or a point value.

Data for US mines were the most detailed. The US Mine Safety and Health Administration (MSHA) takes ventilation air samples at gassy underground coal mine ventilation airshafts on at least a quarterly basis. MSHA provided sampling data for the past two-and-a-half years. Collating the data for each shaft allowed an analysis of ventilation airflow and methane concentration to quantify the range and typical values for those parameters and to illustrate how they vary over time. An understanding of such variation is important when defining operational parameters for a given project (e.g., flow-through capacity, supplemental fuel requirements). It should be noted, however, that although the quarterly data available from MSHA offer valuable insight into flow and concentration variations, project developers will need to obtain such data on an hourly or daily basis to support site-specific project planning.

While other coal-producing countries lacked detailed, shaft-specific VAM characterization data comparable to that obtained from MSHA for US mines, USEPA secured country-level VAM emissions data from open literature and in-country coal-mining experts. These data allowed for similar, albeit less detailed, bottom-up analyses. For the United Kingdom, however, which represents just under 1 percent of estimated world 2000 VAM emissions, key VAM characterization data were unavailable. Thus, for the UK USEPA employed the following “top-down” analytical approach:

1. Used estimates of 2000 overall CMM emissions for developed countries previously published by USEPA (2001).

2. Estimated methane emissions from ventilation systems by adjusting the overall coal-mining emission estimates using country-specific data disaggregating (a) underground from surface mining emissions and (b) methane captured by drainage systems versus methane in the ventilation system.

2.5 Country-Specific Baseline VAM Emission Estimates

To represent the overall ventilation air oxidation market, USEPA attempted to acquire emissions data for major coal-producing countries worldwide. Table 1 lists the study countries in descending order of annual total coal mining-related methane release. These countries comprised 28.3 Bm^3 of total methane release in 2000, or 85.8 percent of worldwide methane emissions from coal mining. Thus, to gain perspective on the overall world market potential for VAM oxidation, USEPA adjusted (increased) the 2000 study country total VAM emissions estimate (14.2

Bm^3) by 17 percent,[7] yielding an overall world total VAM emission estimate for 2000 of 16.6 Bm^3 or 237.1 MMT of CO_2 equivalent (CO_2e). USEPA acknowledges, however, that this estimate of world VAM emissions is only an approximation and that not all of the VAM emissions estimated for the world as a whole or for a given country necessarily will support viable VAM oxidation projects (see section 2.6).

Table 1. Countries Analyzed and 2000 VAM Emissions*

Country**	2000 Methane Emission*** *(Bm^3)*	Percent of World Total	Analysis Performed ^	2000 VAM Emissions *(Bm^3)*	2000 VAM Emissions *(MMT CO_2e)*	Percent of Study Total VAM
China	12.0	36.4	B	6.5	92.3	45.4
United States	5.5	16.5	B	2.5	36.0	17.7
Russia	2.7	8.1	B	0.6	9.2	4.5
Ukraine	2.0	6.0	B	2.1	30.1	14.8
Australia	1.4	4.2	B	0.7	9.5	4.7
Germany	1.2	3.7	B	0.09	1.2	0.6
Poland	1.1	3.3	B	0.4	5.7	2.8
India	0.7	2.1	B	0.3	4.0	2.0
Kazakhstan	0.5	1.5	B	0.3	4.5	2.2
South Africa	0.5	1.5	B	0.4	5.8	2.8
United Kingdom	0.4	1.1	T	0.2	2.2	1.1
Czech Republic	0.4	1.1	B	0.06	0.8	0.4
Mexico	0.1	0.4	B	0.1	1.9	1.0
Study total	*28.3*	*85.8*		*14.2*	*203.4*	*100.0*
Other countries	*4.7*	*14.2*		*2.4*	*33.7*	
World total	***33.0***	***100***		***16.6***	***237.1***	

* Totals may not add due to independent rounding.
** In order of 2000 methane emissions.
*** From USEPA (2001 and 2002c) for developed and developing countries, respectively.
^ B = Bottom-up, T = Top-down

2.6 Uncertainty in the Baseline Emission Estimates

Uncertainties in the baseline emission estimates include the following:

1. For non-US mines with VAM flow and concentration data, the comparability of the mean, average, and typical values reported is uncertain.

[7] 100/85.8 = 1.166.

2. The extent to which the ventilation airflow and methane concentration mean, average, or typical values will represent actual conditions at any given mine is not known. While site-specific conditions likely fall within the ranges provided, a project developer will need to thoroughly characterize VAM flows, concentrations, and variability.

3. The analysis would be improved if VAM flow and concentration data were available for all countries, thereby allowing a comparable bottom-up analysis to be performed in all cases.

2.7 Emissions Projection Methodology[8]

Baseline VAM emission estimates for 2000 provide only a starting point for emission projections. Equipment manufacturers design VAM oxidation equipment to function for almost two decades, with current oxidizer manufacturers expecting an approximate 16-year useful life for their systems. Recognizing that uncertainties associated with coal production and VAM emission projections increase dramatically as the projection timeframe is extended, USEPA selected the period 2000–2020 as the focus of this analysis, thus making the study period consistent with oxidizer manufacturer's expected equipment lifetimes while not unnecessarily increasing analytical uncertainty.

The analytical process for projecting VAM emissions (in the absence of any VAM mitigation efforts) built on the baseline emission estimation methodology described above. For emission estimates using the bottom-up methodology, projections follow these steps:

1. Underground coal production projections were tabulated for the study period. Coal production projections were only available for a few years in the 2000–2020 period, from which production estimates for intervening and subsequent years were interpolated and extrapolated, respectively.

2. For each study country, a VAM specific emission factor was derived from baseline data quantifying VAM emissions and underground coal production for 2000.

[8] Example calculations illustrating the bottom-up and top-down analytical approaches are presented in Appendix B.

3. Future VAM emissions were calculated for each country. Future annual coal production estimates and the VAM emission factors yielded annual VAM emission projections.

For the United Kingdom the top-down emission estimates provided the basis for projecting emissions via the following steps:

1. Future overall coal mining methane emissions were taken from USEPA (2001) that estimated future total coal mining methane emissions for 2005 and 2010.

2. Using data that distinguishes (a) underground from surface mining emissions and (b) methane drained versus methane released from ventilation, VAM emissions were estimated.

3. Emissions were calculated for non-reported years by interpolating and extrapolating from the existing estimates.

2.8 VAM Emissions Projections

Table 2 provides annual, country-specific VAM emission estimates from 2000 to 2020, which reflect expected underground coal production for that period. By providing insight into the rate of growth or decline in expected VAM emissions over time, these projections allowed country-specific estimates of VAM oxidizing capacity requirements, system design specifications, and costs (see section 3.2). Data in the table reveal that, worldwide, VAM emissions are expected to increase by 30 percent between 2000 and 2020 to 308 million tonnes of CO_2e. VAM emission increases are projected to occur in all study countries with the exception of the Czech Republic, Germany, Poland, and the United Kingdom. Projections for China show the greatest absolute increase (to almost 130 million tonnes CO_2e).

2.9 VAM Emissions Projection Uncertainty

Uncertainties in projecting VAM emissions to the year 2020 include:

1. The accuracy of the VAM emissions projections is related directly to the accuracy of the coal production estimates and specific VAM emission factors derived in this analysis.

2. In many countries, uncertainties in the coal industry including privatization, competition from gas-fired power generation, methane management

technology improvements (e.g., directional drilling), and environmental policy affect both coal production and VAM release.

Table 2. Projected Annual VAM Liberation (MMT CO_2e) by Country, 2000–2020

Country*	2000	2005	2010	2015	2020	% Change
China	92.3	101.6	110.9	120.1	129.3	40.1
United States	36.0	39.8	40.6	41.1	39.9	10.7
Ukraine	30.1	37.5	41.3	42.3	43.2	43.3
Australia	9.5	10.5	11.6	12.3	13.6	42.3
Russia	9.2	10.8	11.2	11.6	12.0	29.7
South Africa	5.8	7.0	7.0	7.0	7.0	22.2
Poland	5.7	5.6	5.0	4.8	4.5	-21.6
Kazakhstan	4.5	4.7	4.7	4.7	4.7	5.5
India	4.0	4.5	4.8	5.1	5.4	36.1
United Kingdom	2.2	2.1	2.1	2.0	2.0	-9.6
Mexico	1.9	2.2	1.9	2.0	2.0	4.2
Germany	1.2	1.0	0.6	0.6	0.6	-52.7
Czech Republic	0.8	0.8	0.7	0.6	0.5	-42.8
Study Total	*203.4*	*228.1*	*242.5*	*254.2*	*264.7*	
Other Countries	33.7	37.8	40.1	42.1	43.8	
World Total	**237.1**	**265.9**	**282.6**	**296.3**	**308.5**	

* In order of 2000 VAM emissions

3. Emission Reductions

3.1 Technology Overview

USEPA (2000) identified two technologies for destroying or beneficially using the methane contained in ventilation air: the VOCSIDIZER,[9] a thermal flow-reversal reactor developed by MEGTEC Systems (De Pere, Wisconsin, United States), and a catalytic flow-reversal reactor developed expressly for mine ventilation air by Canadian Mineral and Energy Technologies (CANMET—Varennes, Quebec, Canada). Both technologies employ similar principles to oxidize methane contained in mine ventilation airflows. Based on laboratory and field experience, both units can sustain operation (i.e., can maintain oxidation) with ventilation air having uniform methane concentrations down to approximately 0.1 percent. For practical field applications where methane concentrations are likely to vary over time, however, this analysis assumes that a practical average lower concentration limit at which oxidizers will function reliably is 0.15 percent.

In addition, a variety of other technologies such as boilers, engines, and turbines may use ventilation airflows as combustion air. At least two other technology families may also prove to be viable candidates for beneficially using VAM. These are VOC concentrators and new lean-fuel gas turbines.

3.1.1 Thermal Flow-Reversal Reactor

Figure 5 shows a schematic of the Thermal Flow-Reversal Reactor (TFRR). The equipment consists of a bed of silica gravel or ceramic heat-exchange medium with a set of electric heating elements in the center. The TFRR process employs the principle of regenerative heat exchange between a gas and a solid bed of heat-exchange medium. To start the operation, electric heating elements preheat the middle of the bed to the temperature required to initiate methane oxidation (above 1,000°C [1,832°F]) or hotter. Ventilation air at ambient temperature enters and flows through the reactor in one direction, and its temperature increases until oxidation of the methane takes place near the center of the bed.

[9] VOCSIDIZER is a registered trademark of MEGTEC Systems.

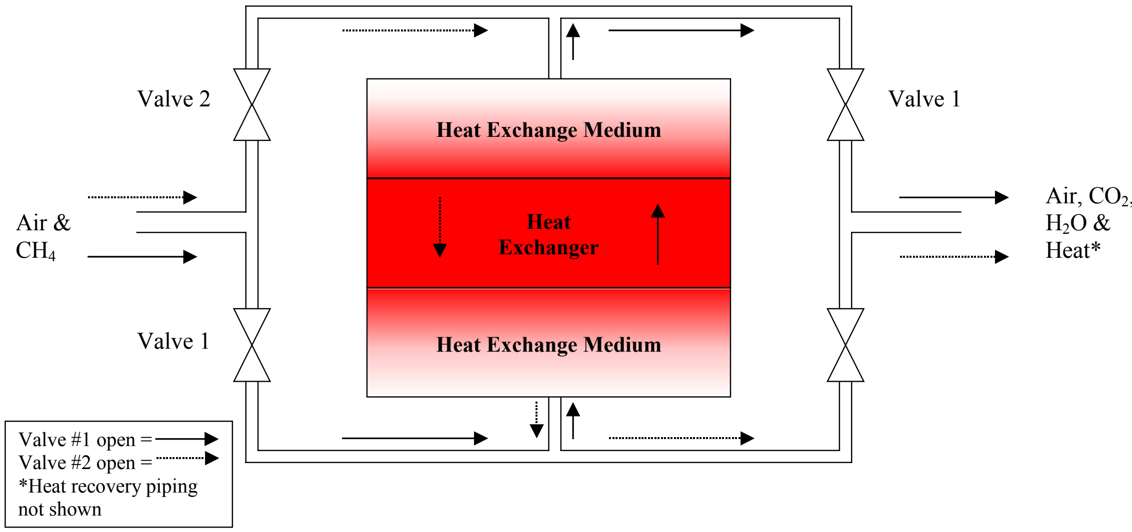

Figure 5. Thermal Flow-Reversal Reactor

The hot products of oxidation continue through the bed, losing heat to the far side of the bed in the process. When the far side of the bed is sufficiently hot, the reactor automatically reverses the direction of ventilation airflow. The ventilation air now enters the far (hot) side of the bed, where it encounters auto-oxidation temperatures near the center of the bed and then oxidizes. The hot gases again transfer heat to the near (cold) side of the bed and exit the reactor. Then, the process again reverses.

As USEPA (2000) points out, TFRR units are effectively employed worldwide to oxidize industrial VOC streams. Furthermore, the ability of MEGTEC's VOCSIDIZER to oxidize VAM has been demonstrated in the field.

3.1.2 Catalytic Flow-Reversal Reactor

Catalytic flow-reversal reactors adapt the thermal flow-reversal technology described above by including a catalyst to reduce the auto-oxidation temperature of methane by several hundred degrees Celsius (to as low as 350°C [662°F]). CANMET has demonstrated this system in pilot plants and is now in the process of licensing Neill and Gunter (Nova Scotia) Ltd. of Dartmouth, Nova Scotia, to commercialize the design (under the name VAMOX).

CANMET is also studying energy recovery options for profitable turbine electricity generation. Injecting a small amount of methane (gob gas or other source) increases the methane concentration in ventilation air to make the turbine function efficiently. Waste heat from the oxidizer is also used to pre-heat the compressed air before it enters the expansion side of the gas turbine.

3.1.3 Energy Conversion from a Flow-Reversal Reactor

There are several methods of converting the heat of oxidation from a flow-reversal reactor to electric power, which is the most marketable form of energy in most locations. The two methods being studied by MEGTEC and CANMET are:

- *Use water as a working fluid.* Pressurize the water and force it through an air-to-water heat exchanger in a section of the reactor that will provide a non-destructive temperature environment (below 800°C [1472°F]). Flash the hot pressurized water to steam and use the steam to drive a steam turbine-generator. If a market for steam or hot water is available, send exhausted steam to that market. If none is available, condense the steam and return the water to the pump to repeat the process.

- *Use air as a working fluid.* Pressurize ventilation air or ambient air and send it through an air-to-air heat exchanger that is embedded in a section of the reactor that stays below 800°C (1472°F). Direct the compressed hot air through a gas turbine-generator. If gob gas is available, use it to raise the temperature of the working fluid to more nearly match the design temperature of the turbine inlet. Use the turbine exhaust for cogeneration, if thermal markets are available.

Since affordable heat exchanger temperature limits are below those used in modern prime movers, efficiencies for both of the energy conversion strategies listed above will be fairly modest. The use of a gas turbine, the second method listed, is the energy conversion technology assumed for the cost estimates in this report. At a VAM concentration of 0.5 percent one vendor expects an overall plant efficiency in the neighborhood of 17 percent after accounting for power allocated to drive the fans that force ventilation air through the reactor.

3.1.4 Other Technologies

This market assessment focuses on the TFRR and CFRR technologies because their vendors are actively pursuing coal mine VAM as a viable market for their equipment. However, USEPA also is in the process of reviewing a number of other technologies that may prove able to play a role in and enhance opportunities for VAM oxidation projects. These are briefly described below.

Concentrators

Volatile organic compound (VOC) concentrators offer another possible economical option for application to VAM. During the past 10 years the use of such units to raise the concentration of VOCs in industrial process-air exhaust streams that are sent to VOC oxidizers has increased. Smaller oxidizer units are now used to treat these exhaust streams, which in turn has reduced capital and operating costs for the oxidizer systems. Ventilation air typically contains about 0.5 percent methane concentration by volume. Conceivably, a concentrator might be capable of increasing the methane concentration in ventilation airflows to about 20 percent. The highly reduced gas volume with a higher concentration of methane might serve beneficially as a fuel in a gas turbine, reciprocating engine, etc. Concentrators also may prove effective in raising the methane concentration of very dilute VAM flows to levels that will support oxidation in a TFRR or CFRR.

There are multiple styles of concentrators employed in industrial applications, with carbon and zeolite wheels generally being the most popular for hydrocarbon reduction purposes. Fluid bed concentrators, however, are expected to offer greater promise for methane concentration. The fluid bed concentrator consists of a series of perforated plates or trays supporting an adsorbent medium (e.g., activated carbon beads). The process exhaust stream enters from the bottom and passes upward through the adsorption trays where it fluidizes the adsorbent medium to enhance capture of organic compounds. The adsorbent medium, which is now heavier because of the adsorbed organic material, falls to the bottom of the adsorber section and is fed to the desorber.


Figure 6. Environmental C & C's Fluidized Bed Concentrator

The desorber increases the temperature of the medium, causing it to release the concentrated organic material into a low-volume, inert gas stream. In this continuous operation, the regenerated medium is fed back to the adsorber vessel for reuse.

Although several vendors offer concentrator systems, Environmental C & C, Inc. (Clifton Park, New York) manufactures the fluid bed concentrator (see Figure 6). With USEPA assistance, Environmental C & C is testing that system's efficacy on simulated VAM using a series of methane-in-air mixtures.

Lean-Fuel Gas Turbines

A number of engineering teams are striving to modify selected gas turbine models to operate directly on VAM or on VAM that has been enhanced with more concentrated fuels, including concentrated VAM (see "Concentrator" section above) or gob gas. These efforts include:

Carbureted gas turbine. A carbureted gas turbine (CGT) is a gas turbine in which the fuel enters as a homogeneous mixture via the air inlet to an aspirated turbine. It requires a fuel/air mixture of 1.6 percent by volume, so most VAM sources would require enrichment. Combustion takes place in an external combustor where the reaction is at a lower temperature (1200°C [2192°F]) than for a normal turbine thus eliminating any NOx emissions. Energy Developments Limited (EDL) of Australia is testing the CGT (see Figure 7) on ventilation air at the Appin coal mine in New South Wales, Australia. EDL is using a modified Solar gas turbine model 3000R (rated at 2.7 MW) for this demonstration.

Figure 7. EDL Carbureted Gas Turbine Installation

Lean-fueled turbine with catalytic combustor. CSIRO Exploration & Mining of Australia, a government research organization, is developing a catalytic combustion gas turbine (CCGT) that can use methane in coal mine ventilation air. The CCGT technology being developed oxidizes VAM in conjunction with a catalyst. The turbine compresses a very lean fuel/air mixture and combusts it in a catalytic combustor. The catalyst allows the methane to ignite at a lower, more easily achieved temperature. As with the CGT, CSIRO's non-conventional turbine will not use combustion air for internal cooling, thus allowing the air intake to contain fuel. CSIRO hopes to operate the system on a 1.0 percent methane mixture to minimize supplemental fuel requirements. CSIRO also will incorporate a latent heat storage system to even out variations in VAM concentration, and is planning for future research and commercialization of the VAM CCGT.

Lean-fuel microturbine. Another US company, Ingersol-Rand Energy Systems, is developing a microtubine that is planned to operate on a methane-in-air mixture of less than 1 percent. This lean-fuel microturbine is a version of their PowerWorks Microturbine System. The microturbine is rated at 70 kW and consists of a generator, gasifier turbine, combustor, recuperator, power turbine, and generator. The system is enclosed in a sound-attenuating enclosure and can be located indoors or outdoors. Ingersol-Rand recently introduced a 250 kW microturbine to the power industry. Additional R&D effort is required to complete the system design on the 70 kW unit and to adapt the 250 kW unit to run in a lean-fuel mode. Ingersol-Rand is seeking funding to further pursue this market.

Lean-fueled catalytic microturbine. Two US companies, FlexEnergy and Capstone Turbine Corporation, are jointly developing a line of microturbines, starting at 30 kW, that will operate on a methane-in-air mixture of 1.3 percent. FlexEnergy, using funding from the US Department of Energy/National Renewable Energy Laboratory and the California Energy Commission, expects to have a 30 kW prototype unit ready for field service in mid-2003. Each unit's components fit inside a compact container that requires no field assembly. The single moving part, rotating on an air bearing, is a shaft on which is mounted the compressor and the turbine expander. Other components include: a recuperator that preheats the VAM mixture, a catalytic combustion chamber with low-temperature ignition, a generator, and a generator cooling section. To better serve the VAM market, FlexEnergy is investigating designs that will reduce required VAM concentration to below 1.0 percent and increase unit sizes to over 100 kW.

Hybrid coal and VAM-fueled gas turbine. CSIRO is also developing an innovative system to oxidize and generate electricity with VAM in combination with waste coal. CSIRO is constructing a 1.2-MW pilot plant that cofires waste coal and VAM in a rotary kiln, captures the heat in a high-temperature air-to-air exchanger, and uses the clean, hot air to power a gas turbine. Depending on site needs and economic conditions, VAM can provide from about 15 to over 80 percent (assuming a VAM mixture of 1.0 percent) of the system's fuel needs, while waste coal provides the remainder. Waste coal and ventilation air enter the rotating kiln in the same direction. The coal's heat of combustion ignites the VAM and a large percentage of that heat is transferred to an air-to-air heat exchanger that operates at about 900°C (1,652°F). Ambient air, pressurized by the gas turbine's (Allison C-18) compressor, flows through the heat exchanger's secondary loop, heats to 900°C, and expands through the turbine's power section. Part of the compressor's output is directed to the turbine cooling path. This system is especially well suited for mines, such as those in

Australia, that generate a significant percentage of waste coal and that can market the lightweight expanded aggregate that is produced in the kiln.

VAM Used as an Ancillary Fuel

While the primary focus of this assessment is on strategies that oxidize major fractions of global VAM emissions, a brief mention of technologies that use VAM only as an ancillary or supplemental fuel is in order. Such technologies rely on a primary fuel other than VAM and are able to accept VAM as all or part of their combustion air to replace a small fraction of the primary fuel. The largest example of ancillary VAM use occurred at the Appin Colliery in Australia, where 54 one-MW Caterpillar engines used mine ventilation air containing VAM as combustion air. Similarly, the Australian utility, Powercoal, is installing a system to use VAM as combustion air for a large coal-fired steam power plant. In addition, the US Department of Energy funded a research project to use VAM in concentrations up to 0.5 percent as combustion air in a turbine manufactured by Solar. Even the CSIRO hybrid coal and VAM project described in the preceding paragraph falls in the category of ancillary VAM use when waste coal combustion is maximized and VAM use is limited to prescribed levels of combustion air.

3.2 Cost Analysis

Although the lowest project costs will be associated with installations that simply oxidize VAM, this analysis assumes that VAM projects will include equipment to allow heat recovery and electricity generation so as to obtain revenues from electricity sales. If energy revenues are insufficient to defray capital and operating costs plus a reasonable profit, they incur a net project cost, expressed as cost per tonne of CO_2e of the abated methane emissions. Unitized net project cost[10] decreases as VAM concentration increases.

This analysis does not take project size, a less influential parameter, into account because small ventilation flows, which occur largely in developing countries, cause only minor cost increases that may be largely offset by lower costs for labor and miscellaneous supplies in these countries.

[10] Project costs were not adjusted to account for local differences in labor costs, tariffs, etc. because the initial system cost estimates available at the time of this assessment were too preliminary for such refinements to be meaningful. Furthermore, it is expected that local costs will have only a minor impact on overall system cost because 1) most of the cost relates to capital costs, which are relatively immune to local cost conditions, and 2) some of these cost differences offset each other (e.g., lower labor cost would be offset by high importation fees). Moving costs are included as O & M cost.

Project costs, for this analysis, are the net present value (NPV)[11] of (1) initial capital cost (including profit), plus (2) annual operating costs, minus (3) revenues from electric power sales. The net project cost of projects implemented at any given VAM concentration represents a marginal cost (i.e., the additional cost that must be offset to make the project profitable). Marginal costs increase with projects having lower and lower VAM concentrations, and one can use marginal abatement cost (MAC) curves to depict this relationship.

To construct a MAC curve for VAM projects, one first must calculate the cost of implementing a project over a range of VAM concentrations and then identify the number of tonnes of VAM abated, within a large sample of VAM emissions, that matches each discrete concentration percentage. To reflect cost differences resulting from changes in VAM concentration, USEPA estimated the net marginal costs (per tonne of CO_2e) for each discrete level of VAM concentration.

$$\text{\$NPV per tonne } CO_2e = \frac{\text{Capital cost} + (\text{\$NPV (O\&M cost - revenues)})}{\text{tonnes } CO_2e \times \text{N years}}$$

USEPA expresses the cost to oxidize VAM (in tonnes of CO_2e) as a net present value (NPV) adjusted to year 0 for all projects analyzed. This method places all projects within a consistent frame of reference so that they are comparable. An alternative would have required a comparison of a particular year's "real-time" cost (e.g., comparing costs for year 1 for a number of projects), but this would have the disadvantage of not being able to account for varying project lives, inflation of various cost and revenue items, and different dates of commencement. NPV carbon emission reduction costs tend to be less than real-time costs, primarily because of the 15 percent discount rate used in this analysis.

The following describes how MAC curve calculations were developed from these cost estimates.

[11] Net present value (NPV) is the combination of capital and operating costs and revenues of a project incurred during the project term discounted to the present (year 0 for each project) using an appropriate discount rate. The formula for calculating NPV is:

$$\text{Present Value} = CF_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \frac{CF_n}{(1+r)^n}$$

where: CF_x = cash flow in period x, n = the number of periods, r = the discount rate.

3.2.1 Methodology

Individual Country MAC Curves

In developing country-specific MAC curves, USEPA used the distribution curve of VAM concentration and flow reported by MSHA for the 58 gassiest ventilation shafts at underground coal mines in the US and adjusted it for application to other countries. Specifically, USEPA employed the following five steps to build the MAC curves, first for the US and next for non-US coal-producing countries.

US MAC Curve—Carbon Mitigation Cost

1. A model was constructed using cost and performance data supplied by the two vendors of flow-reversal technology. The model yielded a net cost, expressed as the NPV of abating VAM emissions, equivalent to one tonne of CO_2. Sensitivity analysis revealed that methane concentration would have the greatest effect on the net oxidation cost of VAM.

2. Net VAM project costs were estimated for VAM concentrations from 0.2 to over 1.0 percent, taking into account the following assumptions:

    - *Discount rate.* While discount rates may vary considerably from country to country, the model used in this analysis applied a 15 percent rate to be conservative and assumed that most projects will be privately sponsored. This rate represents a reasonable average for a private project with blended (i.e., leveraged) debt and pre-tax equity investment. (See further discussion on the discount rate in the “Uncertainties” section below.)

    - *Project size.* The model assumed project airflow capacities of 100 cubic meters per second—large enough to achieve good economy of scale and to fit most modern mining enterprises. In some developing countries where smaller ventilation airflows are common, USEPA assumed that lower prevailing labor costs will tend to cancel out the higher unit costs of smaller plants.

- *Project life.* VAM projects will take place both at bleeder shafts,[12] which tend to have higher VAM concentrations, and at main shafts, which tend to have longer economic lives. The analysis assumed an economic life of 16 years (with project startup occurring in 2002), during which the VAM project modules will have been moved once for a main shaft and three times (every four years) for a bleeder shaft. Moreover, it further assumed that the salvage value of some plant components will likely offset part of the post-project decommissioning costs.

- *Use of gob gas.* System vendors may depend somewhat on gob gas availability, for example to enhance VAM concentration or to raise the temperature of the compressed hot air to reach the design temperatures of a gas turbine. If no gob gas or other supplemental fuels are available, power production will fall off, in some cases substantially, and many mines may not have sufficient gob gas to optimize the performance of every potential project. The analysis included a charge of $1.00 per MBtu ($0.95 per million kilojoules) for the gob gas, but the impact on net project cost is small (i.e., cents per tonne CO_2e), because gob gas use increases the value of revenues from additional power generated. (See the discussion of gob gas availability in the "Uncertainties" section below.)

- *Royalty.* The model did not include any royalty payment to the mine, because it assumed that the mine receives remuneration for its VAM out of project profits.

- *Project debt.* No formal accounting for debt was necessary, because the discount rate accounted for a blend of debt and equity financing.

- *Income tax.* The model assumed a "before tax" return; therefore, it did not address income taxes or depreciation.

- *Electricity sale price.* The model assumed a power price of $0.03 per kWh. Revenues may accrue to a project by calculating the retail value of power savings resulting from the mine purchasing less from its traditional supplier (adjusted by payments for backup, if any), or by selling the power to the

[12] Some mines use bleeder shafts to increase ventilation at individual or groups of longwall panels. Bleeder shafts are smaller in diameter than main mine ventilation shafts (e.g., 4 to 8 feet versus 8 to 28 feet, respectively). Generally, the concentration of methane found in bleeder shafts is somewhat higher (e.g., <2 percent) than that found in main mine ventilation airflows (e.g., <1 percent). Available information indicates that currently only the US and Russia make use of bleeder shafts.

grid. The $0.03 price represents the mid point of anecdotal reports of current pricing in the deep coal-mining regions of the US Rockies and Appalachia.

- *Value of waste heat.* Some of the system configurations being studied by the vendors will produce marketable thermal energy, but the model did not assume any such revenues, since thermal markets could be small, intermittent, or non-existent. Potential uses for thermal energy will depend on site-specific factors that vary worldwide. However, such uses could include coal drying and district heating systems in mining communities. To the extent that projects can take advantage of thermal revenues, the analysis was conservative.

3. A distribution table for VAM emissions was constructed using the VAM flow rates for the US shafts, ranked according to concentration, and grouped by discrete methane concentration percentages according to the following procedure.

   - *Range of VAM concentrations.* The analysis ranked the 58 US ventilation shafts monitored by MSHA in the order of their VAM concentrations, and grouped the shafts into discrete bands of concentration. For example, all projects working with VAM concentrations ranging from 0.15 to 0.25 percent are labeled 0.2 percent, and so on. At concentrations below 0.15 percent, the oxidation units will not be able to sustain the minimum temperature necessary for oxidation (i.e., methane auto-oxidation temperature). Thus, this analysis assumes that 0.2 percent is the lowest practically viable category. The last point on the curve represents the few shafts that have concentrations from 0.95 to over 1.2 percent. To be conservative, this analysis assumed that flows in that range will be 1.0 percent.

4. The results from Step 2 (VAM oxidation costs per tonne of CO_2e) were added to the Step 3 distribution table (for the US a no-power case that does not include the cost of power generation equipment also was developed).

5. The cumulative tonnage of VAM that would be oxidized (if project developers were to take advantage of available opportunities) was plotted against each discrete incremental change in the cost of methane oxidation.

US MAC Curve—Electricity Price

Another way of evaluating the conditions necessary to economically oxidize VAM is to construct a MAC curve that is keyed to the sale price of electricity. The electricity price MAC estimates the number of tonnes of CO_2e that would be mitigated annually using a range of electric prices. Project revenues from the VAM power projects would accrue from electricity sales and do not include carbon mitigation revenues (i.e., a zero cost per tonne of CO_2e).

The US electricity price MAC was constructed in a similar manner to Steps 1 through 3 described under the "US MAC Curve—Carbon Mitigation Cost" methodology, with the following exceptions:

- All financial and cost assumptions remained the same except for the electric price, which became an independent variable.
- Project revenues were assumed to accrue solely from electricity sales.
- A table was created that recorded each pair of VAM concentration and electric price.
- The distribution table of VAM flow rates for US shafts ranked according to concentration (Step 3) was added to the concentration-electric price table assembled above.
- The cumulative tonnage of VAM that could be oxidized was plotted against each discrete incremental change in the price of electricity.

Applying the process outlined above resulted in the MAC curves for the US, which are presented in Figures 8 and 9 (see Section 3.2.2).

Non-US Country MAC Curves

Data from a large sample of gassy ventilation shafts provided airflow volumes and VAM concentrations that made construction of the US MAC curve a fairly straightforward procedure. USEPA received only generalized information from 11 of the other 12 coal mine countries assessed (i.e., shaft-specific data were not available except for some 1995 data from Poland), therefore USEPA used the US distribution curve and adjusted it for application to other countries.

Methane Concentration Distribution

Using the US distribution curve of VAM concentrations should provide a reasonable approximation because US data (1) were derived from a range of coal basins, (2) result from actual field readings, and (3), with data from 58 shafts, should represent a sufficient variability of mines. The following adjustments, however, were made to improve the accuracy of the application of the US MAC curve.

- Concentration percentage ranges. For the UK, where data were unavailable to quantify VAM concentration percentage ranges, the MAC analysis assumed a reasonable range of 0.1–0.7 percent, which is typical of countries that do not employ bleeder shafts.

- Concentration percentage of the median VAM emission rate. This is the concentration at which half of each country's annual VAM flow (volume of methane released per unit time) has a higher concentration and half has a lower concentration. Where the median concentration value was unavailable, the analysis used a value that best approximated this point.

Power Prices

Correspondents in seven countries (including India and South Africa for which MAC curves were not constructed) supplied power pricing information that was useful for generating MAC curves in their respective countries.

- Germany—Radgen (2002) reported that 0.0665 euros (US$0.065)[13] per kWh can be paid for electricity generated at installations with an electrical capacity of over 500 kW using gas from coal mines, and this analysis thus assumed that price for power produced in Germany.

- China—Wenge (2002) gathered data that sampled both wholesale and retail power rates in China. These suggest that US$0.035 may be available for VAM projects.

- Australia—Mallet (2002) supplied actual Australian pricing data, which indicated that a fair price for VAM power would be approximately US$0.02.

[13] Currency conversion based on November 2002 rates.

- United Kingdom—O'Quigley (2002) supplied information indicating that the wholesale electric rate has fallen to about US$0.03 in the UK.

- Ukraine—Filippov (2002) reported that US$0.03 would be a reasonable price to apply for Ukrainian industrial power.

- India—Singh (2002) provided an estimate of what a mine may be willing to pay to a VAM project, which at US$0.07 is the highest estimate encountered in this study.

- South Africa—Lloyd (2002) described energy prices as very low and "likely to remain so." His data supported a price of only about US$0.01 per kWh.

For countries where power pricing information was not available through direct contact with in-country experts, USEPA secured 2001 industrial electricity price data from IEA (2002).

Non-US VAM MAC Methodology

The method for creating a new VAM MAC for each country used the data shown in Appendix A and proceeded as follows:[14]

1. The distribution of US VAM mitigated was ranked and the median concentration was identified (0.39 percent).

2. The cumulative distribution of annual US VAM flow (by concentration) was converted to a percentage distribution.

3. The mid-point of each country's concentrations was identified.

4. A decimal fraction (factor) representing the difference between each nominal increment of the US percentage range and the top and median of the US range was calculated. For example, the US distribution has a span of 0.61 percent from the median of 0.39 percent to the highest concentration grouping of 1.0 percent, while the reported range from China's high of 0.75 percent to its "average" of 0.45 percent spans only 0.3 percent. It is necessary to use a ratio of these US and China spans to distribute the upper half of China's oxidized

[14] A separate calculation was necessary for concentrations above and below the median because reported patterns of mid-points and ranges are not consistent with each other or with the US pattern—an illustrative example of this calculation flow is provided in Appendix B.

methane (in tonnes of CO_2e) according to the US curve, as follows in Steps 5 and 6.

5. The top of each country's concentration range and the difference between that percentage and the median selected in Step 3 were identified.

6. A new concentration range (above the median only) was constructed using the factors developed in Step 4 and the range identified in Step 5.

7. To distribute the bottom half of the curve from the mid-point to the lower end of a country's range, Steps 4, 5, and 6 were repeated.

8. The new concentration range was matched with the NPV cost per tonne of CO_2e by interpolating the US concentration/cost relationships.

9. The new concentration range for each country was matched to the US distribution, as converted to percentages in Step 1.

10. That new concentration percentage distribution was multiplied by the tonnes of VAM (expressed as tonnes of CO_2e) that are emitted by each country.

11. The two series resulting from Steps 8 and 10 become the bases for each country's MAC curves.

The resulting MAC curves for 11 of the 13 countries are in Appendix A. According to information received from India and South Africa, VAM concentrations are generally too low for VAM-fueled oxidation so this study did not produce MAC curves for those countries.

Global MAC Curve

USEPA estimates global emissions of VAM in 2002 to be 247 million metric tons (MMT) CO_2e. USEPA constructed the global MAC curve using the same data as for the county MAC curves, adjusted upward by a factor of 17 percent, which represents the difference between the 11 countries included in the analysis and the global methane emissions from coal mining.[15] The data were combined, sorted, distilled into eleven distinct ranges of NPV cost, and then plotted against

[15] USEPA acknowledges that this adjustment may result in an overestimate or an underestimate of actual total global VAM emissions, but data available at the time of this analysis were not adequate to support a more precise estimate.

cumulative volume of CO_2e. Figures 10 and 11 (see Section 3.2.2) show the global MAC curves.

3.2.2 Analysis of the MAC Curves

To interpret the information provided in a MAC curve, one can select a specified value of emission reduction value (e.g., Y-axis in Figure 8) or electric power price (e.g., Y-axis in Figure 9) and then read the expected emissions reductions (on the X-axis) from the appropriate curve. To provide perspective on the relationship between electric power sales revenue and overall project cost and profitability, note that Figure 8 includes a second cost line that represents the unitized cost of methane abatement in the absence of any electric power sales.

Two MAC curves are provided for each country individually and all study countries grouped at the global level. One MAC curve depicts the amount of methane that can be oxidized at a given carbon value ($ per tonne of CO_2e) assuming a fixed electricity sales price. A second curve is provided to illustrate the methane oxidation potential at various electricity prices where power generation is the only revenue source.

US MAC Curves

The US MAC curves (see Figures 8 and 9) offer a valuable frame of reference for estimating the effect of changes in net project costs. In the US a relatively low net project cost (marginal cost) could make profitable VAM oxidation projects that would remove much of the mine ventilation methane currently released to the atmosphere. For example, Figure 8 reveals that a marginal cost of $2.00 per tonne of carbon dioxide equivalent (net present value) could subsidize a reduction of almost 7 MMT annually.

The upper curve in Figure 8 represents projects that have no opportunity to produce electricity and are installed without generating equipment (i.e., with oxidizers only). The lower curve represents projects that benefit from both power production and emissions reduction, and include power generation costs. In most cases, carbon dioxide mitigation costs are higher for projects without power generation potential due to the absence of power revenues. As the capital cost burden of power generation equipment increases, however, carbon mitigation costs for power production projects can exceed those of oxidation-only projects. In Figure 8 this is illustrated where the two curves converge (and even cross) because of a decreasing effect from electric power sales coupled with the capital cost burden of power generation equipment for the lower curve. This is because the quantity of

VAM (going from left to right and expressed as CO_2e oxidized) increases as a function of CO_2e oxidation costs. The upper end of the curve represents projects oxidizing the lower VAM concentrations. Therefore, in the oxidation-with-power-production case, net electric power revenues for these projects decrease because more and more oxidizer energy must be used to operate the fans (i.e., parasitic loss) relative to the volume of inflowing methane. With less electric power revenue, more subsidy is needed per tonne of CO_2e oxidized, so the curve tends to become steep at the upper end.

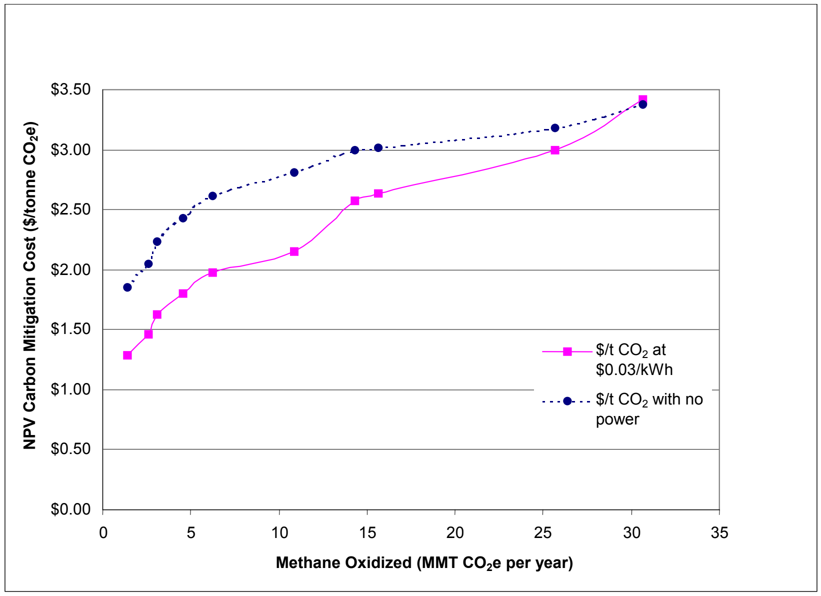

Figure 8. MAC Analysis for the United States—Carbon Mitigation

It is also possible to estimate how a change in emission reduction value will create opportunities for additional projects. For example, if the price to mitigate a tonne of carbon dioxide equivalent were to rise from $2.00 to $3.00 it would create an incremental US market for economically sustainable projects that would reduce annual emissions by more than 25 MMT of carbon dioxide equivalent. Such increases in emission reduction value can improve the economics of already profitable projects or could transform economically unattractive projects into ones that are worth pursuing.

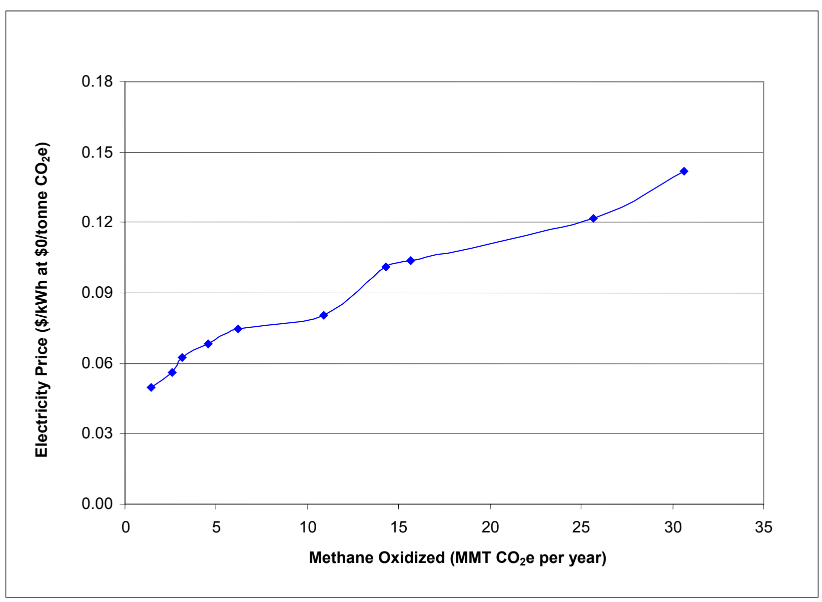

Figure 9. MAC Analysis for the United States—Power Production

Figure 9 illustrates the relationship between the electric power price received by a VAM project and the level of carbon emission reductions it could achieve. CO_2e oxidized increases only as a function of higher electric

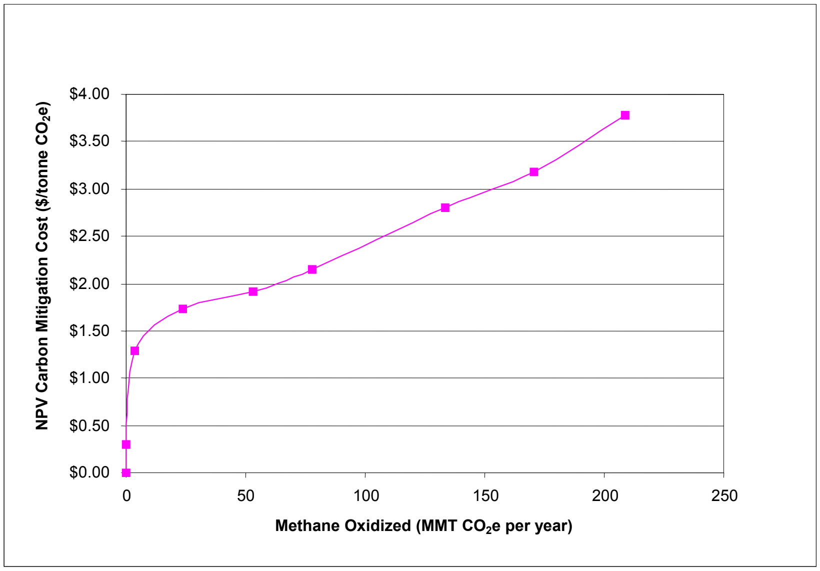

Figure 10. Global MAC Analysis—Carbon Mitigation

prices. At the upper end ever higher prices are needed to overcome the rising effects of parasitic losses.

With a low electric price, only projects with high VAM concentration would be implemented in the US. Conversely, a very high electricity price would be sufficient to support projects that might oxidize most of the available VAM in the US at concentrations as low as 0.2 percent. In the US, projects would need to secure power revenues at a minimum of about $0.05 per kWh to begin making VAM oxidation viable.

Global MAC Curves

The global MAC curves (see Figures 10 and 11) cover project opportunities in all countries with underground mining. They can be read in the same way as the US curves. For example, Figure 10 illustrates that with a marginal carbon abatement cost of about $2.00 one might expect affordable VAM projects to oxidize over 60 MMT of CO_2e annually. At $3.00, almost 160 MMT of CO_2e could be oxidized per year, which represents nearly a 100-MMT increment due to the one-dollar marginal cost rise. Figure 11 reveals that globally, if project revenues derive only from electricity sales, substantial levels of VAM emission mitigation begin to be feasible if electric power prices exceed $0.06 per kWh.

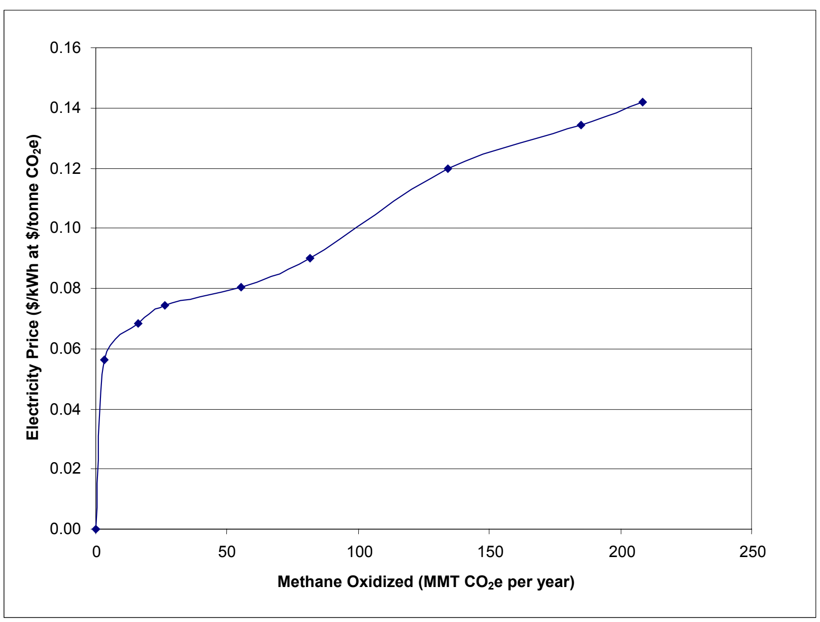

Figure 11. Global MAC Analysis—Power Production

3.2.3 Opportunity Cost of VAM Recovery and Use

Fluctuations in the price of electricity will affect the overall profitability of a project, and thus the minimum acceptable price of carbon recovery. Such fluctuations may be caused by market forces, negotiated contracts, or the restructuring or privatization process that many transitional countries are undergoing. Regardless of cause, electricity prices will vary over time. Thus it is useful to display the MAC analysis results in terms of opportunity costs that illustrate the relationship between varying electricity prices and carbon costs at different levels of VAM recovery. Figure 12 provides such an opportunity cost graph for the global market. Opportunity cost graphs also are provided for each study country in Appendix A.

In countries where 50 percent of the country's CMM is available at a concentration of 0.39 percent or more, the costs per ton of CO_2 equivalent dip into the negative values at higher electricity prices. But the project-specific VAM concentration must be higher than 0.8 percent and the price of electricity greater than US$0.06. For countries below the 0.39-percent CMM concentration threshold, carbon prices in all cases will be positive.

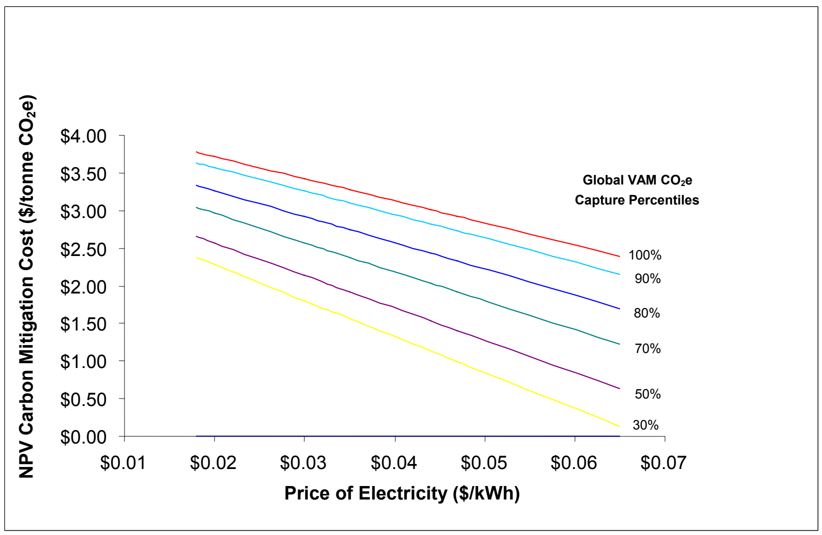

Figure 12. Global Opportunity Cost Curve

The opportunity curves display a cumulative relationship for the amount of VAM capturable at a given electricity price level and the corresponding carbon emission mitigation cost. This is shown ranked by percent of global VAM captured, thus the tenth percentile represents the highest quality of VAM capturable. On the graphs displaying the opportunity cost relationships for each country shown in Appendix A, the median value is indicated as a highlighted line.

The trend in these opportunity charts indicates that, should the value of carbon emission reductions be sufficient, electricity generation would not be needed. The NPV price of CO_2e mitigated in this analysis ranges from US$2 to US$4.

3.2.4 VAM Carbon Mitigation Cost in the Absence of Power Generation

As the opportunity curves show (see Figure 12), VAM mitigation projects are viable at low electricity prices, with the corresponding carbon emission mitigation costs within a currently reasonable market range. Figure 13 provides perspective on carbon emission mitigation costs for the US that would result from VAM oxidation projects that do not include electric power generation (i.e., projects where no turbine is purchased and no power is sold).

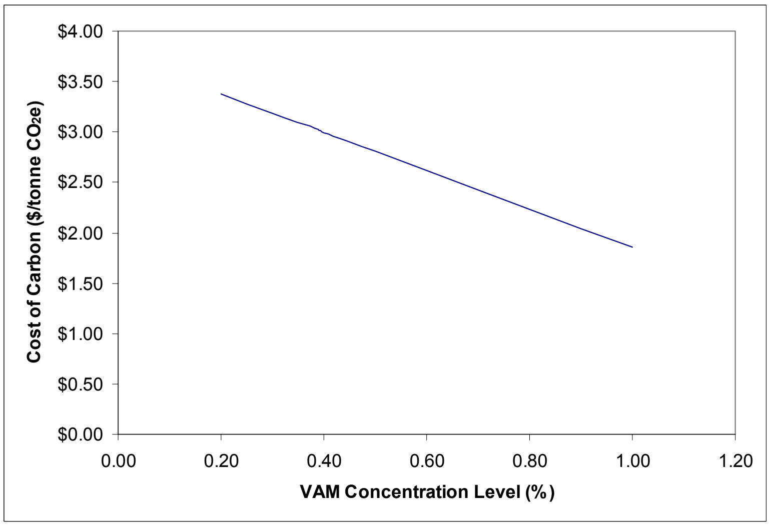

Figure 13. US Carbon Mitigation Cost in the Absence of Power Generation

Figure 13 shows the carbon emission mitigation costs that would be associated with projects oxidizing various VAM concentrations. As would be expected, lower VAM concentrations equate with higher carbon emission mitigation unit costs.

3.2.5 Uncertainties

A number of uncertainties underlie the assumptions used in this analysis. Some of these uncertainties will tend to increase the estimated cost of VAM oxidation, while others will result in lower cost estimates. The discussions presented below describe the significance of each uncertainty and, where possible, explain how the study has attempted to mitigate the impact of each on the MAC curves.

Cost Implications

This analysis reflects a host of factors that affect VAM project costs, as is discussed below.

- *Conservatism in the analysis*. This analysis employed conservative assumptions as necessary in the absence of requisite data elements or in interpreting and adopting existing data to meet analytical needs, and that conservatism tended to increase estimated costs. Therefore, it is expected that as the uncertainties that required such assumptions are resolved, VAM oxidation cost estimates will decrease as compared with those reflected herein.

- *Technology maturation*. As VAM oxidation technologies mature and are employed in coal producing countries, economies of scale may drive down manufacturing costs somewhat. Similarly, new technologies for productively using VAM may evolve over time that are less costly (in terms of either capital or operating cost) than those reviewed in this analysis.

- *Plant downtime*. The costing model used to develop the MAC curves allows for a 10-percent downtime to cover scheduled and unscheduled plant outages. Thus, any downtime in excess of 10 percent will raise project costs above those considered in the model, while downtime below 10 percent will reduce project costs. Cost-constrained project economics will likely prohibit a facility from adding a unit to cover downtime and raise plant availability to near 100 percent.

- *Shaft transitions*. Plant designers will select ventilation shafts that appear to have a reasonably long economic life (four years or more) so that the plant does not have to relocate too frequently. Before each move, however, it is possible that some shafts will not maintain expected VAM flows, or conversely, after each move some may not reach expected flows. Both circumstances would increase costs and reduce revenues.

- *Moving interval and time*. The MAC analysis estimated that periods between moves would be four years for bleeder shafts and eight years for main shafts. If each relocation, including dismantling, transporting, and reassembling, were to use up two months, lost time would amount to about 4 percent and 2 percent for the bleeder and main shafts, respectively.[16] Shorter move intervals will decrease revenues and increase costs; shorter move times will increase revenues and decrease costs.

- *Siting difficulties*. Some ventilation shaft evasés are located in areas that may be unsuitable or unavailable for transporting and installing the heavy, large components of a VAM project. Such constraints could involve difficult

[16] These estimates are approximations based on dialogue with Brian King, Senior Consultant, Neill & Gunter (Nova Scotia-Canada) Ltd., Dartmouth, Nova Scotia, Canada.

access roads and steep inclines, and either could add to capital and moving costs.

- *Development delay*. In the real world of project development, considerable delay occurs between the time a project becomes an economically viable candidate and the day it commences commercial operation. When delay becomes extreme, it can add to project capital costs.

- *Institutional issues*. For a variety of reasons (e.g., financial instability, inability to strike an agreement with a developer) not every potential mine host will welcome a project. Some of these issues may work out over time, but the solutions might subject the project to higher fees, interest costs, or operating costs.

- *Lack of capital*. In some areas of the world, project opportunities have difficulty finding affordable investment capital, so the cost of capital could rise for those projects that do receive funding.

- *Political and domestic issues*. History suggests that some countries encounter unsettled periods when it is difficult to implement sound, profitable ventures that take advantage of otherwise attractive project development opportunities. To bring about projects in spite of such eventualities, the developer may incur additional costs.

- *Currency fluctuations*. Changes in the currency exchange rate over time may constitute a significant cost issue in international projects.

VAM Data

The first source of uncertainty has to do with the VAM characterization data available for each country under evaluation. Data gathered by MSHA were the basis for US VAM characterization.

For VAM information from other countries, the analysis relied on data from in-country coal mining industry experts. Current, detailed projections of VAM production rates and methane concentrations were sometimes available. Where data gaps existed, USEPA used conservative assumptions to project or interpolate values. Appendix A contains country-specific details.

The extent to which the extrapolation from study country VAM emission totals to world VAM emission totals, based on the ratio of 2000 overall coal mining methane emissions for the study countries versus the global total, results in an accurate world estimate is unknown.

Probability of Declining and Fluctuating Ventilation Airflow or VAM Concentration

A review of several years' VAM data from gassy US mines revealed significant fluctuations in shaft-specific ventilation airflow and VAM concentration. If the airflow decreases while the concentration holds steady, a developer might be able to stage a gradual plant relocation to a new shaft, using most modules during the transition.

To account for expected transitions, the analysis allocated a reasonable amount to a reserve fund in the economic model to cover plant moving costs every four years for bleeder shafts and eight years for main shafts. Note that, while the continuity of concentration and flow over time varies at the shaft level, the overall national-level concentrations and flows are relatively constant.

A number of factors affecting the market will change over time, including:

- Amount of coal mined
- Ratio of VAM released per unit of coal mined
- Quantity of methane drained from the vicinity of active mining
- Portion of overall liberated VAM exiting a given shaft, especially in the later years of a shaft's economic life
- Ventilation airflows
- VAM concentrations

Variations in methane flows and concentrations are a function of and are determined by mining conditions underground, and these parameters will not be changed to accommodate VAM oxidation project needs at the surface. Only by carefully observing recent history and understanding current mine plans can a project manager create a strategy that is as immune to such variability as possible. At some mines drained but unused methane (e.g., gob gas) may be available to serve as a supplemental fuel to reduce variations in VAM concentration (estimates of the total amount of CMM available in each study country are provided in the country analyses in Appendix A). In the absence of supplemental fuel, without very high subsidies a project cannot afford to install modules that would sit idle for significant periods, so the plant size typically will match below-average anticipated flows. For the most variable shafts this would leave substantial intermittent VAM flows unabated. After viewing the standard deviation averages for US shafts grouped according to airflow and VAM flow, USEPA assumes that this phenomenon would amount to 20–25 percent of the VAM for each project. The shafts with higher air and VAM flow rates exhibit less variability, quarter to quarter, than do shafts with the smaller flows.

Concerns remain about the potential for dips or gradual declines in VAM concentration, even while the host shaft is still functioning at full flow. The Appin Colliery project in Australia presents a real example of this phenomenon. VAM concentration there declined for several years after the project first started, due, according to one account (Bray, 1999), to the degasification effects of a drainage program. A developer might be able to define the risk of reduced VAM by gaining an understanding of the long-term mine plan and then budgeting accordingly.

Assumed Heat Rate

Heat rate is the ratio of energy (in this case VAM) flowing into a system to that flowing out (in this case electricity). The MAC curves presented herein reflect a typical heat rate developed from information provided by oxidizer manufacturers and an assumed VAM concentration. However, in practice VAM concentrations at a given project site may be significantly higher or lower than the assumed value, and such variation would have marked effect on the actual heat rate achieved. If other factors are constant, projects oxidizing lower VAM concentrations would encounter higher parasitic losses due to the need to move large volumes of ventilation air through the system to assure an adequate VAM flow to the oxidizer. This would degrade (increase) the heat rate. Alternatively, projects encountering higher VAM concentrations could be expected to achieve improved (decreased) heat rates.

New Technological Application

While oxidizers have been commercially deployed for many different industrial applications, neither Neill and Gunter (Nova Scotia) Ltd.'s catalytic VAMOX system nor MEGTEC's thermal VOCSIDIZER has operated at full commercial scale at an underground coal mine, and small pilot demonstrations have not yet been equipped to produce electric power. Therefore, certain aspects of their operation remain to be demonstrated. For example, the vendors' ability to build and operate an efficient and reliable heat exchanger in very hot reactor environments appears to be feasible but not absolutely certain. As a result of such technical uncertainties and the lack of actual pilot plants, USEPA asked the two system vendors to provide realistic yet conservative estimates of system performance and economic projections at various levels of VAM concentration. While overall system (oxidizer, heat exchanger, and power production) costs are still somewhat uncertain, a large amount of work has gone into engineering studies and cost estimates.

Availability of Gob Gas

As mentioned above, many project sites could have insufficient gob gas to optimize the performance of every potential project. For such cases, several options now or soon may exist to compensate for gob gas shortfalls. These include:

- Installing a concentrator in the ventilation airflow to create an auxiliary fuel source
- Redesigning the prime mover in one of several ways to reduce the need for auxiliary fuel
- Operating the power generator at a lower output
- Purchasing natural gas or another suitable fuel

The inclusion of gob gas at $1.00 per MBtu in the model is probably a reasonable estimate for cases where gob gas is available and for the first two options listed above. The last two options listed above will have the net effect of significantly raising the cost of projects using VAM to generate electricity.

Selection of a Realistic Power Price

A VAM project with electricity-generation capability will need a substantial and predictable revenue stream from power sales to be credible with potential sources of financial support. A project can either export its power to the grid or sell it to the host mine who would then reduce power purchases from the local utility and pass the savings along to the project entity. However, small producers that sell to the grid may not obtain full value for their power because, in the US for example, markets usually prefer blocks of power amounting to over 50 MW while most VAM projects could only produce about 10–15 MW. Also, while selling to the host mine could displace the higher retail price normally paid by the mine, the developer will have to assure the mine owner that back-up power purchased during periods when the project is off-line will not use up any savings offered by the project.

The findings from this preliminary research effort for both exported and self-generated power could not be supported by a statistically valid database. However, USEPA selected a conservative average price of $0.03 per kWh for US projects, and that is consistent with prices mentioned in informal discussions held during the preparation of this report.

It should be noted that in most countries it may not be possible to count on a steady power price for the entire project duration because prices react to ever-changing demand and supply conditions. Since the project's financial backers will require assurance that the expected revenue stream from power sales is secured contractually (at least through the term of the project loan), project developers will need to execute long-term power sales agreements.

For further discussion on the basis for the power price, see Appendix C.

Uncertainties Relating to Financial Assumptions in the Model

To select financial assumptions to complete this analysis, USEPA faced several issues. The first was the question of what discount rate to use. One reasonable approach would be to assume a leveraged financing where a 15 percent discount rate might represent a blend of 75-percent debt at 9 percent plus a 25-percent equity share earning a pre-tax internal rate of return (IRR) of 33 percent. The 15-percent rate may be conservative for projects that can leverage higher than 75 percent, obtain a lower interest rate on debt capital, or accept a slightly lower IRR.

Second, using depreciation and income tax calculations in the economic analysis proved difficult because of the great variety of financing structures and tax profiles of developers most likely to implement a VAM project. Therefore, USEPA modeled all scenarios on a pre-tax basis. While this decision offers a transparent and simple analysis, it produces somewhat conservative estimates when compared to the anticipated cost savings that will accrue to developers who use creative financial structures to gain tax-loss credits in the project's early years.

A third issue involves the project term, for which the analysis used a 16-year economic life. These power projects will probably realize a small salvage value for reusable equipment at the end of the project's economic life, but that value may be offset with decommissioning costs, so no salvage value was assumed. This assumption appears to be a realistic match to the plant's true economic life. In summary, the analysis used conservative values for all of the three key economic modeling assumptions, so it offers an overall conservative outcome.

3.2.6 Estimating the Effects of Uncertainties on the MAC Curves

The study's uncertainties affect the accuracy of the economic models and the resulting accuracy of the MAC curves. The following points offer some perspective on the impact of these on the actual implementation of VAM projects.

- *Questions of cost.* If the cost models have underestimated or overestimated the cost of oxidizing a tonne of CO_2e (or the energy revenues), the effect will be to delay or accelerate the implementation of projects that match each discrete level of CO_2e value. However, such cost/revenue forecasting problems should not affect the overall MAC concept or the shape of the curves.

- *Questions of average field data.* The MAC analysis is susceptible to possible over- and underestimates of VAM flow data, on a shaft-by-shaft basis, because most US (MSHA) readings reflect only one day per quarter, and no overseas data were available for individual shafts. Taken as a whole, however, the flow data probably represent a fair picture of the market.

- *Questions of available supplemental fuel.* Some concern may exist about the availability of gob gas or other supplemental fuel, which is needed for optimal performance of some technologies. As discussed previously, technologies exist that may prove able to cost-effectively concentrate VAM to use as a fuel supplement or to allow the plants to achieve acceptable efficiencies with less supplemental fuel.

- *Questions of flow and concentration variability.* An analysis of airflow and concentration for 58 US ventilation shafts showed a slight bias for increased variability as airflows became smaller. The data were significantly affected, however, by the variation of shafts that were either just starting up or nearing their end. Project managers should be able to cope with most of the effects of variability by being fully aware of mine plans.

The MAC curves described above should offer encouragement to the firms and individuals who hope to abate the largest source of CMM emissions, ventilation air methane. With a comprehensive set of actual emission data from the majority of US VAM, the analysis used reliable cost and performance information based on many years of engineering by two vendors of VAM oxidation technology.

3.2.7 Worldwide Market Potential

If all VAM on the MAC curve costing less than $3 per tonne of CO_2 were mitigated with the installation of power projects, a substantial number of projects would come into being and offer a sizeable market for hardware and important economic activity. Table 3 presents forecasts of the net electric power capacity sales and revenues that would be created by all feasible VAM projects in each country (based on estimated emissions in 2002).

Table 3. Potential Worldwide Market for VAM Projects (at under $3.00/tonne CO_2e)

Country*	Total 2002 VAM Emissions (Bm^3)	2002 VAM Emissions <$3.00 Tonne CO_2e (Bm^3)	Net Electric Capacity (MW)	Equipment Sales (US$000,000)	Annual Revenue (US$000,000)
China	6.7	5.47	1,365	3,802	431
United States	2.6	1.81	457	1,213	124
Ukraine	2.2	1.13	264	912	71
Russia	0.7	0.61	141	498	56
Australia	0.7	0.37	96	243	17
Poland	0.4	0.26	52	258	22
Kazakhstan	0.3	0.04	11	29	2
United Kingdom	0.2	0.13	31	96	8
Mexico	0.1	0.10	27	62	11
Germany	0.08	0.07	16	63	9
Czech Republic	0.06	0.04	5	54	2
*Study Totals***	*14.8*	*10.04*	*2,464*	*7,229*	*754*
Other Countries	2.5	1.7	409	1,199	125
World Totals	**17.3**	**11.7**	**2,873**	**8,428**	**880**

* In order of 2002 VAM emissions

** Numbers may not equal totals due to rounding.

As the table reveals, China alone theoretically could create 1,365 MW of net useable capacity, almost half of the world total of 2,979 MW. Assuming the equipment value for each project (sized at a nominal 100 m^3-per-second airflow) equals approximately $10 million, the possible world total equipment market estimate would be $8.7 billion. Finally, the annual revenue column estimates net power revenues (i.e., power produced minus parasitic power consumed by the plant) from each country. These revenues, which are functions of VAM concentrations and power prices, total $908 million annually.

4. SUMMARY AND CONCLUSIONS

This report estimates the market potential for oxidizing ventilation air methane worldwide using newly available technology that can operate on VAM concentrations down to a practical limit of 0.2 percent to produce useable energy. To quantify the current and future US market USEPA used current, detailed VAM data at the ventilation shaft level. Non-US data were, to varying degrees, incomplete and generalized. To complete country-by-country and global characterizations, the analysis used overseas data with the US distribution curve of VAM flow versus concentration. The analysis then combined these results with project cost estimates supplied by system vendors to construct marginal abatement cost curves.

The MAC curves for the 11 countries that appear to have viable project opportunities (presented in Appendix A) indicate a significant potential for the development of VAM projects worldwide. They demonstrate that the cost of VAM oxidation is low. The curves indicate that at an NPV cost of $3.00 per tonne of carbon dioxide equivalent projects could abate almost 160 million tonnes of CO_2 annually.

Of course these marginal abatement cost estimates will improve as actual installations provide increasingly reliable VAM emissions and project cost data. But the uncertainties that affect each step of this analysis should not detract from the report's basic message: that large-scale VAM use offers a low-cost opportunity to reduce greenhouse gas emissions.

5. REFERENCES

Bray (1999): E-mail communication with Geoff Bray, President, Bray Solutions Pty Limited, Oyster Bay, New South Wales, Australia, November 1, 1999.

Filippov (2002): E-mail communication with Alexander Filippov, Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine, January 16, 2002.

Filippov (2002): E-mail communication with Alexander Filippov, Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine, June 25, 2002.

IEA (2002): Fourth quarter 2001 (or later) data obtained from the International Energy Agency web site (http://www.iea.org/statist/keyworld2002/key2002/keystats.htm).

IPCC (2001): *Climate Change 2001: The Scientific Basis*, Intergovernmental Panel on Climate Change, Cambridge University Press, New York, United States.

Lloyd (2002): E-mail communication with P.J.D. Lloyd, Energy Research Institute, University of Cape Town, Cape Town, South Africa, September 12, 2002.

Mallet (2002): E-mail communication with Dr. Cliff Mallett, Commonwealth Scientific and Industrial Research Organization, Kenmore, Queensland, Australia, October 15, 2002.

O'Quigley (2002): E-mail communication with Philip O'Quigley, Energy Finance Limited, Dublin, Ireland, November 21, 2002.

Radgen (2002): E-mail communication with Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany, October 15, 2002.

Singh (2002): E-mail communication with Umesh Prasad Singh, Deputy Chief Engineer, Coal India, Ltd., Calcutta, India, September 27, 2002.

USEPA (2000): *Technical and Economic Assessment: Mitigation of Methane Emissions from Coal Mine Ventilation Air,* US Environmental Protection Agency, Office of Air and Radiation, EPA-430-R-001, February 2000.

USEPA (2001): *Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990–2010,* US Environmental Protection Agency, Office of Air and Radiation, EPA-430-R-01-007, December 2001.

USEPA (2002a): *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2000*, US Environmental Protection Agency, Office of Atmospheric Programs, EPA-430-R-02-003, April 15, 2002.

USEPA (2002b): *US Inventory Changes—Revision 2*, working draft, US Environmental Protection Agency, Office of Atmospheric Programs, January 3, 2002

USEPA (2002c): *Non-CO_2 Greenhouse Gas Emissions from Developing Countries: 1990–2020,* US Environmental Protection Agency, Draft, February 2002.

Wenge (2002): E-mail communication with Liu Wenge, Project Manager, China Coalbed Methane Clearinghouse, Beijing, China, August 20, 2002.

APPENDIX A
COUNTRY-SPECIFIC ANALYSES
(2000–2020)

This appendix details the process employed in estimating country-specific current and future ventilation air methane emissions. It specifies data sources, explains assumptions, and discusses country-level uncertainties. Table A provides an overview of the input data used and the VAM estimation results obtained for all countries evaluated.

Each country discussion provides background information on a country's underground coal mining industry and potential VAM release. An explanation follows of the data sources used and specific methodology employed in estimating current and future VAM emissions.

Table A. Summary of VAM Liberation Projections, 2000–2020

Country	VAM Release (m^3 per tonne)	VAM Conc. (%)	Airflow m^3/s		2000	2005	2010	2015	2020	% Change
China (Bottom-up analysis)				10^6 tonnes UG coal prod.	949.1	1045.0	1140.0	1235.0	1330.0	
	6.80	Range: 0.0-0.75	Range: 16.7-333.3	Bm^3 VAM	6.5	7.1	7.8	8.4	9.0	
		Typical: 0.3-0.6	Average: 161	MMT CO_2e	92.3	101.6	110.9	120.1	129.3	40.1
		Average: 0.46								
United States (Bottom-up analysis)				10^6 tonnes UG coal prod.	338.2	373.3	381.4	385.8	374.5	
	7.45	Range: 0.1-1.6	Range: 17-1,833	Bm^3 VAM	2.5	2.8	2.8	2.9	2.8	
		Median: 0.388	Median: 214.4	MMT CO_2e	36.0	39.8	40.6	41.1	39.9	10.7
Ukraine (Bottom-up analysis)				10^6 tonnes UG coal prod.	79.2	98.5	108.7	111.1	113.5	
	26.6	Range: 0.1-0.6	Range: 51-215	Bm^3 VAM	2.1	2.6	2.9	3.0	3.0	
		Typical: 0.2-0.4	Average: 133	MMT CO_2e	30.1	37.5	41.3	42.3	43.2	43.3
		Average: 0.3								
Australia (Bottom-up analysis)				10^6 tonnes UG coal prod.	63.6	69.8	77.0	82.1	90.4	
	10.50	Range: 0.1-0.7	Range: 150-300	Bm^3 VAM	0.7	0.7	0.8	0.9	0.9	
		Average: 0.4	Average: 225	MMT CO_2e	9.5	10.5	11.6	12.3	13.6	42.3
Russia (Bottom-up analysis)				10^6 tonnes UG coal prod.	63.5	74.0	76.8	79.6	82.3	
	10.18	Range: 0.0-0.75	Range: 1.4-295	Bm^3 VAM	0.6	0.8	0.8	0.8	0.8	
		Average: 0.38	Average: 43	MMT CO_2e	9.2	10.8	11.2	11.6	12.0	29.7
South Africa (Bottom-up analysis)				10^6 tonnes UG coal prod.	142.1	173.7	173.7	173.7	173.7	
	2.83	Range: 0.05-0.2	N/A	Bm^3 VAM	0.4	0.5	0.5	0.5	0.5	
		Mean: 0.1		MMT CO_2e	5.8	7.0	7.0	7.0	7.0	22.2
Poland (Bottom-up analysis)				10^6 tonnes UG coal prod.	102.1	101.0	90.0	85	80.0	
	3.91	Range: 0.1-0.4 (1993); 0.1-0.7 (2000)		Bm^3 VAM	0.4	0.4	0.4	0.3	0.3	
		Wt. ave. 8 gassy mines: 0.259	Wt. ave. 8 gassy mines: 221	MMT CO_2e	5.7	5.7	5.0	4.8	4.5	-21.6

Country	VAM Release (m^3 per tonne)	VAM Conc. (%)	Airflow m^3/s		2000	2005	2010	2015	2020	% Change
Kazakhstan (Bottom-up analysis)				10^6 tonnes UG coal prod.	8.2	8.7	8.7	8.7	8.7	
	38.30	Range: 0.07-0.5	Range (4 shafts): 150-221	Bm^3 VAM	0.3	0.3	0.3	0.3	0.3	
		Mean: 0.29	Average (4 shafts): 185.5	MMT CO_2e	4.5	4.7	4.7	4.7	4.7	5.5
India (Bottom-up analysis)				10^6 tonnes UG coal prod.	69.1	78.2	84.0	89.0	94.0	
	4.02	Range: 0.1-<0.3	Range: 10-40	Bm^3 VAM	0.3	0.3	0.3	0.4	0.4	
		Typical: 0.1	Typical: 40 at large mines	MMT CO_2e	4.0	4.5	4.8	5.1	5.4	36.1
United Kingdom (Top-down analysis)				10^6 tonnes UG coal prod.	~25					
	12.2	N/A	N/A	Bm^3 VAM	0.2	0.1	0.1	0.1	0.1	
				MMT CO_2e	2.2	2.1	2.1	2.0	2.0	-9.6
Mexico (Bottom-up analysis)				10^6 tonnes UG coal prod.	4.8	5.4	4.8	5.0	5.0	
	28.36	Range: 0.4-0.8	Range: 91-197	Bm^3 VAM	0.1	0.2	0.1	0.1	0.1	
		Average: 0.5	Average: 140	MMT CO_2e	1.9	2.2	1.9	2.0	2.0	4.2
Germany (Bottom-up analysis)				10^6 tonnes UG coal prod.	31.7	26.0	15.0	15.0	15.0	
	2.75	Range: 0.08-0.8	N/A	Bm^3 VAM	0.09	0.07	0.04	0.04	0.04	
		Average: 0.3		MMT CO_2e	1.2	1.0	0.6	0.6	0.6	-52.7
Czech Republic (Bottom-up analysis)				10^6 tonnes UG coal prod.	14.9	13.7	11.8	10.0	8.5	
	3.91	Range: 0.1-0.7		Bm^3 VAM	0.06	0.05	0.05	0.04	0.03	
		Wt. ave.: 0.259	Wt. ave.: 221	MMT CO_2e	0.8	0.8	0.7	0.6	0.5	-42.8
			Study Total	MMT CO_2e	203.4	228.1	242.5	254.2	264.7	
			Other Countries	MMT CO_2e	33.7	37.8	40.1	42.1	43.8	
			World Total	MMT CO_2e	237.1	265.9	282.6	296.3	308.5	

VAM OXIDATION MARKET POTENTIAL: CHINA

Background

China ranks number one in world coal production and is responsible for over 45 percent of the total VAM emissions from the countries evaluated in this analysis. China's coal industry is expected to remain strong over the next two decades to meet the energy needs of its rapidly growing economy. It has large reserves of gassy, high-rank coal that contain coalbed methane (CBM) resources estimated at twice those of the US, and its overall coal mine methane (CMM) emissions are the largest worldwide. Exploitation of China's coalfields will expand over time as the country strives to upgrade the size, safety, and efficiency of its mines.

Roughly 85–90 percent of methane released to the atmosphere from coal mining in China originates in underground mines, with about 88 percent of that total exiting via mine ventilation systems. In 1999, approximately 6 billion m^3 of methane was released to the atmosphere from ventilation systems (Zhu, 2001).

Business Climate

China is the world's most populous country, with a rapidly growing economy that has led to sharp increases in energy demand. Growth in electricity consumption is projected at 5.5 percent per year through 2020. The largest gainer in terms of fuel share in the future is expected to be natural gas, due largely to environmental concerns in China's rapidly industrializing coastal provinces. If a truly competitive market for electric power develops as planned, the Chinese market may become attractive to foreign investment.

China is currently attempting to upgrade the size, safety, and efficiency of its mines, and part of that process involves a concerted effort to develop its CMM resources. Chinese companies with gassy coal mine assets are actively seeking potential project developers and investors. China and the US are cooperating to identify and support the commercialization of CMM projects. To date, that initiative has identified eight mining companies that have both attractive CMM resources and

China 2000 Data Summary

UG Coal Production (MMT)		949.1
Unit VAM Release (m^3/tonne)		6.8
VAM Concentration (percent)		0.5*
Average Shaft Ventilation Airflow (m^3/sec.)		161.0*
VAM Emission:	MMT CO_2e	92.3
	Bm^3	6.5
Drained CMM Available (Mm^3/yr)		220

* Average

market potential and thus that appear to offer the best CMM project development opportunities in China. For each mine, development plans and utilization markets have been documented and are now available to international investors. Further support is being offered by the Asian Development Bank, which will allocate US$200 million to finance CBM and CMM projects in the country. This strong desire to secure support and partnership for developing a range of CMM development projects, including power generation, may offer a positive business climate for VAM oxidation and electricity generation. In fact, some Chinese mining companies, such as the Yangquan Coal Group, have acknowledged that they are anticipating future application of VAM oxidation technologies once economic feasibility is proven (World Coal, 2001).

Methodology

Zhu (2002) reported typical ventilation airflow rates for small and medium mines that range from 16.7 to 83.3 m^3 per second (averaging 50 m^3 per second), for large mines that range from 83.3 to 166.7 m^3 per second (averaging 125 m^3 per second), and for very large very gassy mines that range from 166.7 to 333.3 m^3 per second (averaging 250 m^3 per second). Zhu also quantified underground coal production for each mine class for the years 1999 and 2000. Those coal production data reveal that, in China, the trend in underground coal production is moving away from smaller mines toward larger mines. The share of coal production from such large mines grew almost 10 percent from 1999 to 2000. Zhu (2001) reported that the average VAM emission rate per unit coal production in China is 6.8 m^3 per tonne of coal produced. He also provided a VAM concentration range of 0.0–0.75 percent, with typical concentrations ranging from 0.3 to 0.6 percent. Wenge (2002) provided additional data characterizing ventilation air at gassy underground mines in China. His data indicate an average VAM concentration of 0.46 percent and an average ventilation airflow rate of 161 m^3 per second. Being of more recent origin, the values reflected in the data provided by Wenge were used for this analysis. Zhu (2002) reported under-

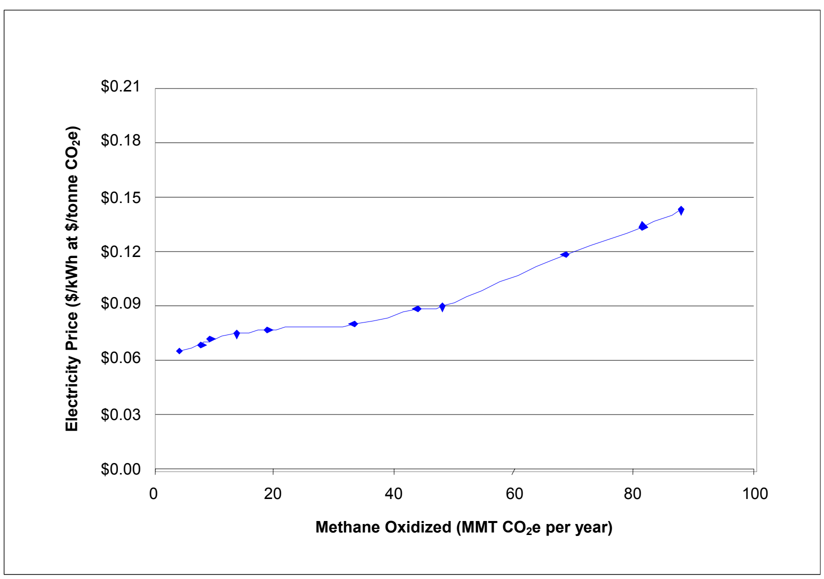

Figure A-1. MAC Analysis for China—Power Production

ground and surface coal production levels for 1999 and 2000, and Zhu (2001) reported total coal production projections for 2005 and 2015. USEPA interpolated and extrapolated from those coal production data points to estimate future annual coal production for the 2000–2020 study period. The 1999 and 2000 coal production data revealed that roughly 95 percent of coal produced in China is mined underground. Because future coal production projections were not disaggregated, USEPA used the 95-to-5 ratio (underground to surface) reported for the 1999–2000 period to project future underground production.

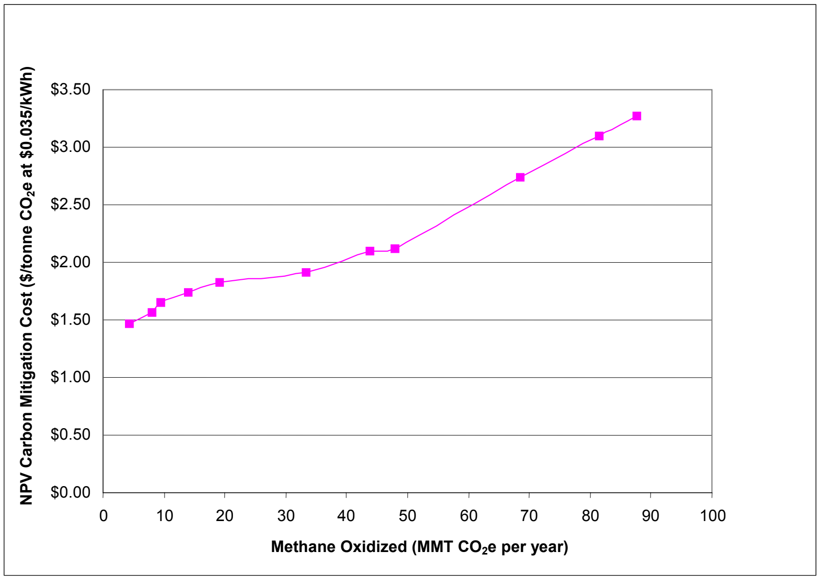

Figure A-2. MAC Analysis for China—Carbon Mitigation

Applying the 6.8 m^3 per tonne coal VAM emission rate to the annual underground coal production projections yielded annual VAM emissions in Bm^3, which were then converted to units of MMT of CO_2e.

Data from Huang (2002) quantifying CMM degasification and utilization in China in 2000 revealed that over 220 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- Zhu (2001) reports that increased exploitation of deeper, gassy mines over time will likely increase the average volume of methane released per tonne of coal produced nationwide

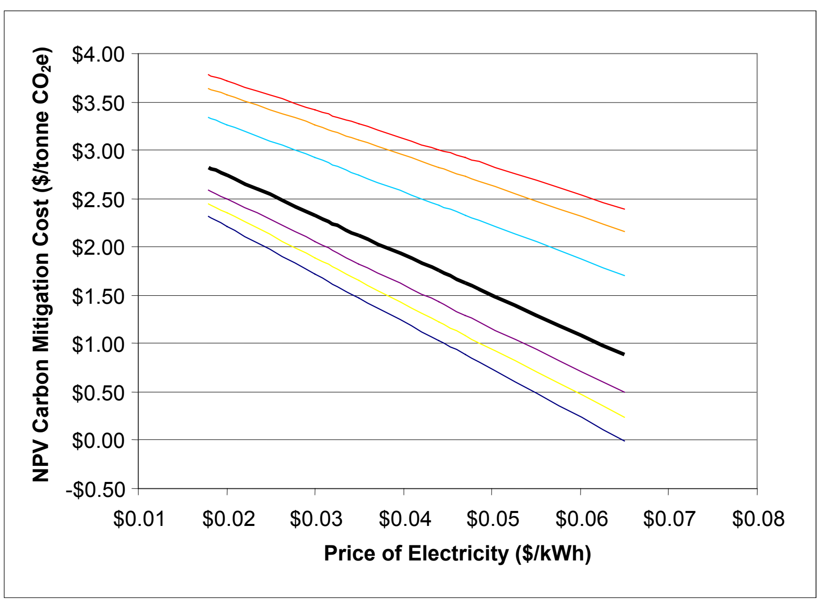

Figure A-3. Opportunity Costs for China

between now and 2015. Thus, using the current ratio to estimate the level of methane released per tonne of coal produced may underestimate future releases.

- Projections of the actual expected mix of production from small versus medium versus large underground mines would provide a better basis for calculating an average value for ventilation airflow.

- Estimates of the trend in surface to underground coal production through the study period would improve the VAM emission projections.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in China, which emits almost 40 percent of the world's VAM, could theoretically create 1,365 MW of net useable capacity, almost half of the world total of 2,979 MW. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for China would be almost $4 billion. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $430 million.

References

Huang (2002): "Potential for Commercial Development of Coal Methane in China," paper presented by Huang Shengchu, Vice President, China Coal Information Institute, China Coalbed Methane Clearinghouse, at the 2001 International CMM/CBM Investment and Technology Symposium, Shanghai, China, 2001.

Wenge (2002): E-mail communication with Liu Wenge, Project Manager, China Coalbed Methane Clearinghouse, Beijing, China, October 17, 2002.

World Coal (2001): "Reducing CBM in Yangquan Coal Field," *World Coal,* March 2001, Volume 10, Number 3.

Zhu (2001): E-mail communication with Zhu Chao, China Coalbed Methane Clearinghouse, Beijing, China, July 31, 2001.

Zhu (2002): E-mail communication with Zhu Chao, China Coalbed Methane Clearinghouse, Beijing, China, February 7, 2002.

VAM OXIDATION MARKET POTENTIAL: UNITED STATES

Background

In recent years, US mines have begun to employ an innovative means of underground coal mine degasification: the use of small-diameter bleeder shafts at longwall coal mines. Used in conjunction with main mine ventilation shafts, bleeders provide supplemental ventilation in the immediate vicinity of longwall faces. USEPA (2000) provides an overview of the use of main mine ventilation shafts versus bleeders, which use much smaller airflows and typically have higher VAM concentrations, offering particularly attractive opportunities for VAM project development.

Business Climate

The US is the world's largest energy producer, consumer, and net importer. US power demand is increasing rapidly, with a forecasted 1.8 percent average annual growth in electricity sales through 2020. This increase will require a significant addition in generating capacity. The US has more experience with CMM recovery than any other nation. In 2000 the US emitted over 4.0 Bm^3 of CMM from underground coal mines and recovered 86 percent, or over 1.0 Bm^3, of the gas liberated through drainage systems. This represents an almost three-fold increase from the less than 0.4 Bm^3 recovered in 1990 (USEPA, 2002a).

United States 2000 Data Summary

UG Coal Production (MMT)		338.2
Unit VAM Release (m^3/tonne)		7.4
VAM Concentration (percent)		0.4*
Average Shaft Ventilation Airflow (m^3/sec.)		214.4*
VAM Emission:	MMT CO_2e	36.0
	Bm^3	2.5
Drained CMM Available (Mm^3/yr)		250

* Median

Methodology

To predict US VAM emissions over time, USEPA accessed detailed, historical, mine-specific ventilation emissions data. Average VAM concentration and ventilation airflow values were derived from US Mine Safety and Health Administration (MSHA) ventilation shaft sampling data, reported for 58 gassy mine shafts that are monitored quarterly by MSHA. Although different mines had varying numbers of quarterly sampling results, data for multiple quarters were available in all cases.

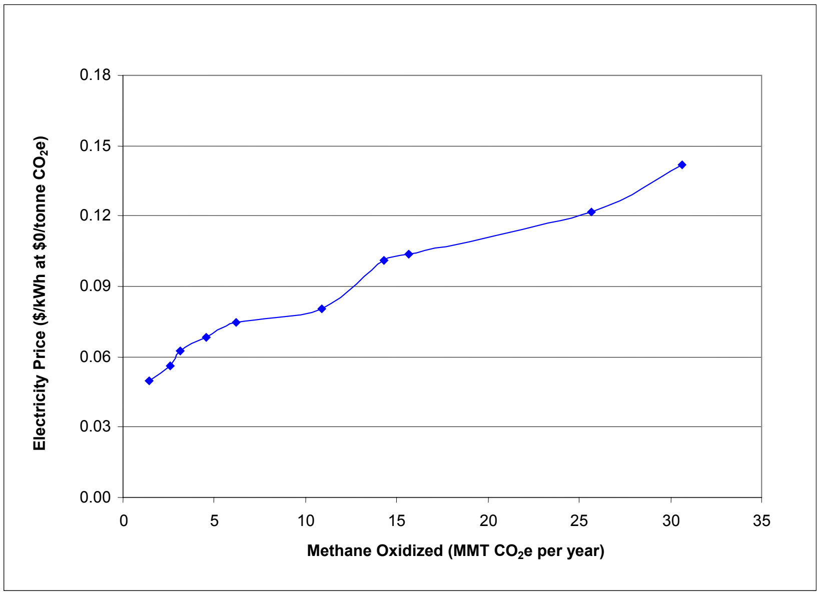

Figure A-4. MAC Analysis for the United States—Power Production

USEPA (2002b) lists underground coal production for 2000 (372.8 million short tons; 338.2 million tonnes) and ventilation system methane emissions for 2000 (2.5 Bm^3) from which USEPA derived a unit VAM emission rate of 7.45 m^3 per tonne. The US Energy Information Administration (2001) quantified underground coal production for 2005, 2010, 2015, and 2020. Interpolation from those data provided production estimates for intervening years. USEPA projected annual VAM emission estimates by applying the unit VAM emission rate to the annual underground coal production estimates. In developing MACs that reflect likely VAM oxidation market potential in the US, however, the total VAM emission level reported in USEPA (2002b) was reduced to reflect the fact that the gassy mines surveyed by MSHA and that have VAM flows for which oxidation is technically feasible are responsible for approximately 82 percent of total US VAM emissions.

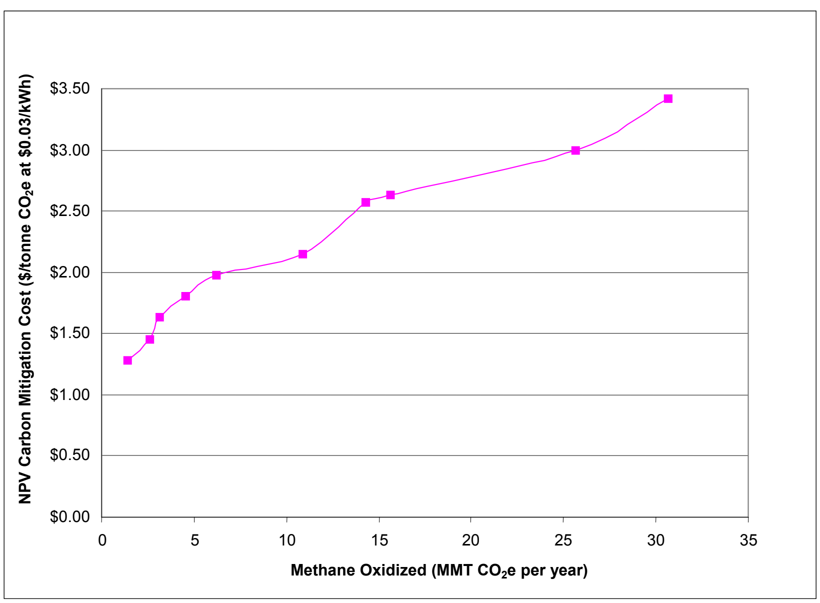

Figure A-5. MAC Analysis for the United States—Carbon Mitigation

Data from USEPA (2002c) quantifying CMM degasification and utilization in the US in 2000 revealed that approximately 250 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- The mine-specific data obtained from MSHA offered highly detailed insight into the characteristics of VAM flows from gassy mines in the US, as well as some understanding of the variability over time of those flows. Thus, the US analysis is based on the most detailed data of any of the country analyses.

- An analysis of airflow and concentration for 58 US ventilation shafts showed a slight bias for increased variability as airflows became smaller. The data were significantly affected, however, by the variation of shafts that were either just starting up or nearing their end. Project managers should be able to cope with most of the effects of variability by being fully aware of mine plans.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in the US, which emits over 15 percent of the world's VAM, could theoretically create 457 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for the US would be over $1.2 billion. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $120 million.

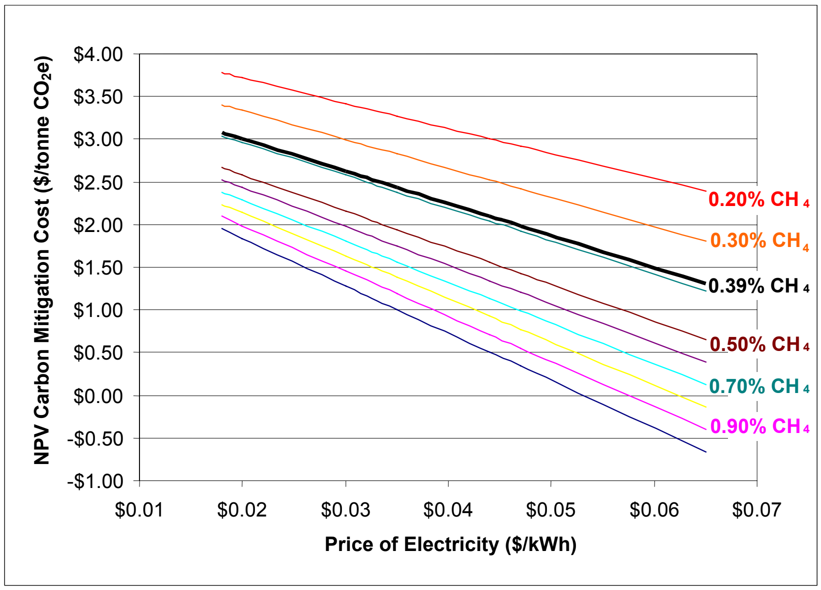

Figure A-6. Opportunity Costs for the United States

References

USEIA (2001): *World Energy Outlook,* US Energy Information Administration, December 12, 2001.

USEPA (2000): *Assessment of Potential Lifetime of a Methane Oxidation System on Main and Longwall Bleeder Shafts,* Coalbed Methane Outreach Program publication, October 2000. Available online at http://www.epa.gov/coalbed.

USEPA (2001): *Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990–2010,* US Environmental Protection Agency, EPA-430-R-01-007, December 2001.

USEPA (2002a): Data retrieved from internet site, http://www.epa.gov/coalbed/about.htm, July 2002.

USEPA (2002b): *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2000*, US Environmental Protection Agency, Office of Atmospheric Programs, EPA-430-R-02-003, April 15, 2002.

USEPA (2002c): *US Inventory Changes—Revision 2*, working draft, US Environmental Protection Agency, Office of Atmospheric Programs, January 3, 2002.

VAM Oxidation Market Potential: Ukraine

Background

Commercialization and rationalization of the coal industry in Ukraine has yet to be accomplished. State subsidies for unprofitable mines substantively influence coal markets, for example by requiring coal to be sold to utilities and other "strategic users" whether they can pay or not (World Coal, 2000). Eight mines were scheduled for privatization in 1999, but the fact that the state would retain majority holdings in each frustrated that process. Although the state owns coal mines and coal resources, including methane (Triplett et al., 2001), mines can be leased, as many successful mines are.

In 2000, Ukraine had 232 active coal mines, of which all but three were underground workings (Triplett et al., 2001). Even though the industry faces substantial challenges deriving from the lack of commercialization and reform, annual coal production is expected to grow. Filippov (2002) provided total coal production projections for 2001 through 2005 and for 2010. He cited subsequent annual increases in total coal production anticipated at 120–125 million tonnes per year by 2030. Interest in developing the country's CBM resources has grown markedly in recent years, as has the search for investors who can develop projects for pipeline gas injection or other beneficial use.

Filippov (2000) reported VAM concentrations at Ukrainian mines ranging from 0.1 to 0.6 percent (the lower value is the sensitivity limit of the methane detectors being used), with typical values ranging from 0.2 to 0.4 percent. He noted that 0.75-percent methane is the maximum allowable concentration (measured at the top of the ventilation shaft) and observes that, although such higher concentrations do occur, they are abnormal events. Triplett (2002) observed that bleeder shafts currently are not employed in Ukraine, probably because the average working depth of mines there is over 700 meters.

Ukraine 2000 Data Summary

UG Coal Production (MMT)		79.2
Unit VAM Release (m^3/tonne)		26.6*
VAM Concentration (percent)		0.3**
Average Shaft Ventilation Airflow (m^3/sec.)		133**
VAM Emission:	MMT CO_2e	30.1
	Bm^3	2.1
Drained CMM Available (Mm^3/yr)		130

*Weighted average

** Average

Filippov (2000) also quoted a ventilation airflow range from 51 m^3 per second to 215 m^3 per second (reflecting the range of flow rates evidenced at a sample of about 30 mines) and observed that a given mine may have from two to five ventilation shafts in place. Methane emissions in Ukraine declined from almost 3.9 Bm^3 in 1990 to over 2.0 Bm^3 in 2000.

Business Climate

Ukraine's energy sector is plagued by a lack of domestic energy sources, increasing foreign debt, and outdated and inefficient equipment. The country's electric consumption was 146.7 billion kWh in 1999. In 1998 and 1999 new laws and decrees improved the business climate for CBM/CMM development by making CBM production projects potentially eligible for certain tax benefits, by establishing legal and civil commitments relating to natural resource development in Ukraine, and by establishing Free Economic Zone status in the Donbass region to provide for tax incentives that can attract investment there. Recently the Partnership for Energy and Environmental Reform (PEER), with support from the USEPA, made available an inventory of Ukrainian CMM emissions and a Ukrainian coal mine development handbook. In addition, to date PEER also has developed business plans for two of the 29 mines addressed by the handbook. Thus, at present the regulatory and tax environments in Ukraine are more favorable than they ever have been for CBM/CMM development. However, in 2000 Ukrainian mines captured 12.4 percent of the total methane liberated, and only 27.9 percent of the methane captured was utilized. These low percentages of methane capture and use result from inadequate funds being available for proper gas collection system maintenance or to support new development projects.

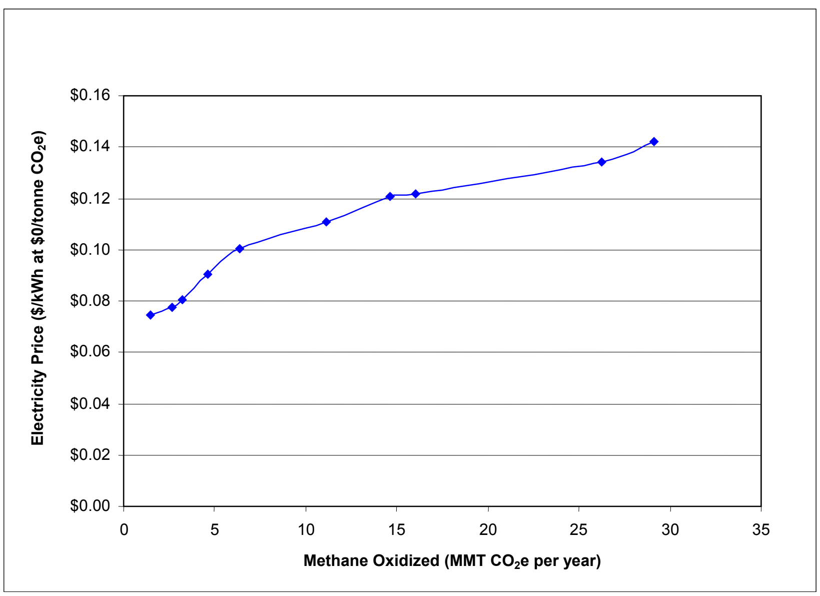

Figure A-7. MAC Analysis for Ukraine—Power Production

Methodology

Partners In Economic Reform (PIER, 2000) reports that underground coal production is responsible for 98.5 percent of the total in Ukraine. PEER (2002a) provided underground coal production and ventilation system methane emissions for 2001 and 2002, from which a weighted average specific VAM emissions value of 26.6 m^3 per tonne was derived.

Production estimates for 1999–2020 were interpolated and extrapolated from the annual production reported by Filippov (2002). Using these projections and the 1999 underground-to-total coal production ratio of 98.5 percent, the analysis developed annual underground coal production estimates. The VAM emission rate was then applied to the estimated annual underground coal production levels to estimate annual VAM emissions.

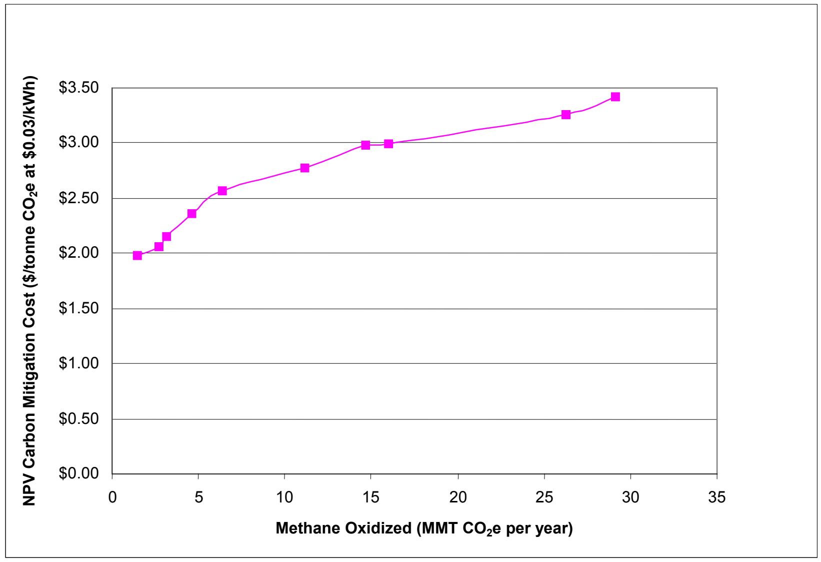

Figure A-8. MAC Analysis for Ukraine—Carbon Mitigation

Data from PEER (2002b) quantifying CMM degasification and utilization in Ukraine in 2000 revealed that over 130 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- Expansion of coal mine methane drainage could result in lower VAM emissions in future years, but no data are available to quantify such reduction.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Ukraine, which emits over 12 percent of the world's VAM, could theoretically create 264 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Ukraine would be over $910 million. Finally, the

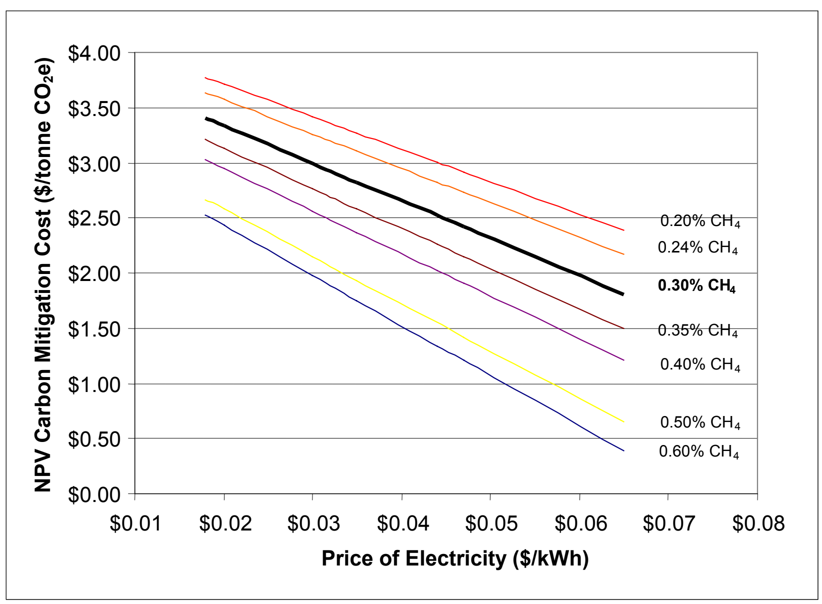

Figure A-9. Opportunity Costs for the Ukraine

annual revenues that could accrue from such power sales in the country could amount to over $70 million.

References

Filippov (2000): E-mail communication with Alexander Filippov, Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine, December 20, 2000.

Filippov (2002): E-mail communication with Alexander Filippov, Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine, January 16, 2002.

PEER (2002a): Coal production and ventilation system methane emission data provided by Partnership for Energy and Environmental Reform, Kiev, Ukraine, August 2002.

PEER (2002b): Data obtained from the Partnership for Energy and Environmental Reform website at http://www.peer.org.ua/New-1.html.

PIER (2000): *Inventory of Methane Emissions from Coal Mines in Ukraine: 1990–1999*, Partners In Economic Reform, Incorporated, prepared in cooperation with the Alternative Fuels Center, Kiev, Ukraine, sponsored by the US Environmental Protection Agency, August 2000.

Triplett (2001): E-mail communication with Jerry Triplett, Partnership for Energy and Environmental Reform (PEER), Kiev, Ukraine, September 13, 2002.

Triplett et al. (2001): Jerry Triplett, Alexander Filippov, and Alexander Pisarenko, *Coal Mine Methane in Ukraine: Opportunities for Production and Investment in the Donetsk Coal Basin,* January 2001.

World Coal (2000): *Industry in Motion*, *World Coal,* February 2000, Volume 9, Number 2.

VAM OXIDATION MARKET POTENTIAL: AUSTRALIA

Background

Mutmansky (2002) observed that, in general, Australian underground coal mining practices closely resemble those in the US and that coal seam characteristics (thickness, etc.) also are similar. Australian mining companies have led the world in demonstrating techniques to oxidize VAM. At the Appin Colliery, BHP Engineering Pty. Ltd. with Energy Developments Ltd. (EDL) gathered VAM from a ventilation shaft evasé and used it as combustion air for 54 one-MW Caterpillar engine-generators (Bray, 1998). More recently, Australian engineers are designing and testing a number of promising VAM-use technologies. At one mine site BHP and MEGTEC Systems recently demonstrated the use of a VOCSIDIZER unit on VAM and extracted thermal energy from the reactor bed in the form of low-pressure steam. That project has been dismantled, and a commercial-scale demonstration is being designed under the Australian Greenhouse Gas Abatement Program (GGAP). EDL is developing a lean-fueled, carbureted gas turbine that will operate on a methane mixture of 1.6 percent. The CSIRO Exploration & Mining of Australia has two technologies under development. The first is a lean-fueled turbine with a catalytic combustor. The system will introduce a 1.0 percent fuel/air mixture into the air intake, compress it, combust it in the catalytic combustor, and expand it through the turbine. The other system is a hybrid system that cofires waste coal and VAM in a rotary kiln, captures the heat in a high-temperature air-to-air heat exchanger, and uses the clean, hot air to power a gas turbine. Powercoal, an electric utility, has another noteworthy project in the planning stage. The company will link the air intake of the Vales Point coal-fired power station to two mine ventilation systems (Endeavour and Munmorah Collieries) and use the VAM to supplement the station's fuel supply.

Australia 2000 Data Summary

UG Coal Production (MMT tonnes)		63.6
Unit VAM Release (m^3/tonne)		10.5
VAM Concentration (percent)		0.4*
Average Shaft Ventilation Airflow (m^3/sec.)		225*
VAM Emission:	MMT CO_2e	9.5
	Bm^3	0.7
Drained CMM Available (Mm^3/yr)		50

*Average

Business Climate

Australia's energy consumption habits are similar to those of the United States and Canada. Australia's energy demand increased about 3 percent per year during the 1990s, but has slowed to under 2 percent in 2001 and 2002.

Australia produces in excess of 55 percent of its electrical power from domestic coal. Being relatively clean, Australia's coal can be burned without incurring high costs for sulfur control, and this contributes to the low cost of electricity in the country.

Through the Greenhouse Gas Abatement Program (GGAP), Australia is actively promoting implementation of activities that will reduce greenhouse gas emissions and sequester carbon. To that end, the program is making \$24 million available to two projects that will capture and combust methane to produce electricity at three underground coal mines in Queensland and New South Wales. Those projects are expected to result in reductions of over 1 million tonnes of methane release per year.

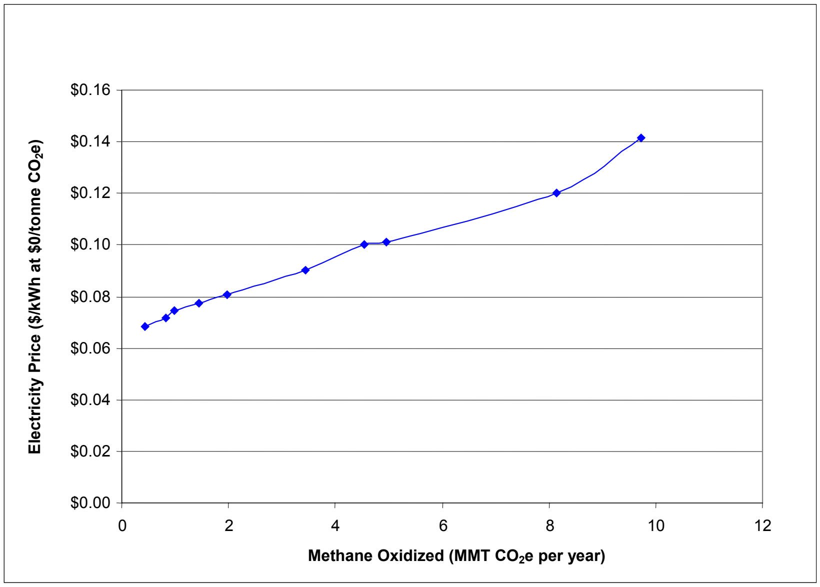

Figure A-10. MAC Analysis for Australia—Power Production

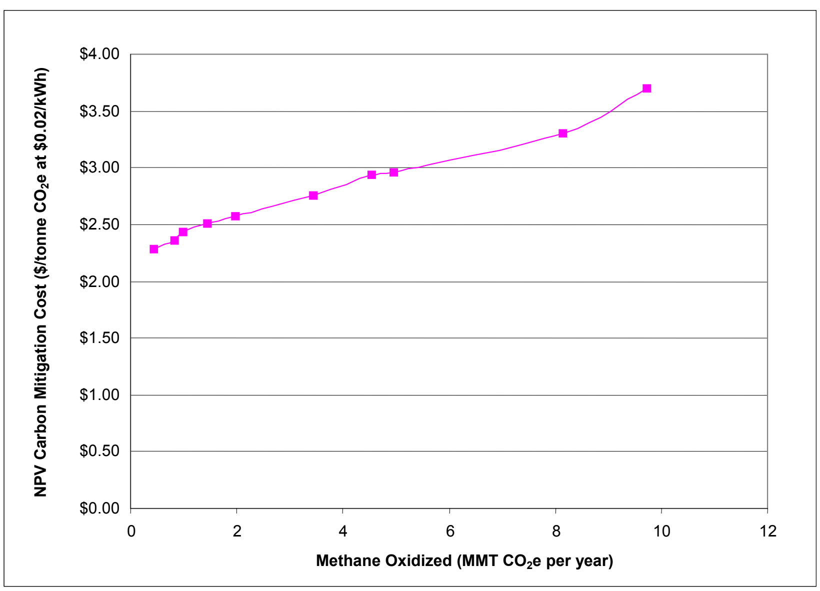

Figure A-11. MAC Analysis for Australia—Carbon Mitigation

Methodology

Wendt et al. (2000) undertook a study of the potential to use coal mine methane exiting Australia's underground coal mines in drainage and ventilation systems. That study reported typical ventilation airflow rates of 150–300 m^3 per second and VAM concentrations of 0.0–1.0 percent, with typical flows in the 0.1 to 0.7 percent range, and noted that safety regulations mandate that VAM concentrations be less than 1 percent in main ventilation air returns. From those data, USEPA calculated average parameter values to be 0.4 percent for concentration and

225 m^3 per second for flow. Wendt et al. also reported annual surface and underground coal production data for the country, which revealed that 27.5 percent of coal mined in Australia originated at underground mines in 1997–1998. Furthermore, Wendt et al. cited VAM specific emissions for a subset of underground mines along with coal production data for those mines. From those data USEPA calculated a weighted average specific emissions value of 10.5 m^3 VAM per tonne of coal mined.

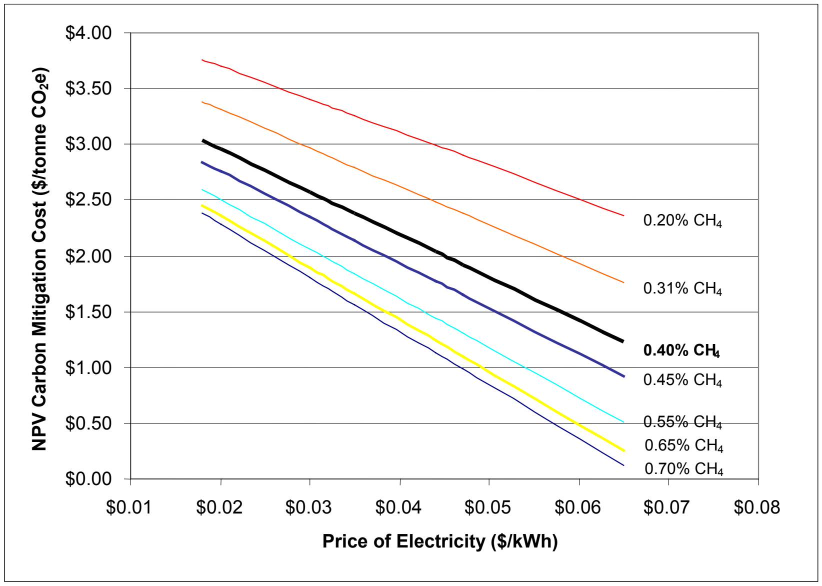

Figure A-12. Opportunity Costs for Australia

To estimate future annual VAM emissions, USEPA first adjusted total (surface and underground) national coal production projections from Saghafi (2002) for 2000, 2005, 2010, 2015, and 2020 by a factor of 27.5 percent to estimate future production from underground coal mines. The VAM specific emissions value then was applied to the coal production estimates to estimate annual VAM emissions for those five years. USEPA interpolated from those estimates to obtain VAM emissions for the intervening years.

Data from USEPA (2001) quantifying CMM degasification and utilization in Australia in 2000 revealed that over 50 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- The extent to which the surface to underground coal production ratio reported for 1997–1998 will accurately represent the actual situation throughout the 2000–2020 study period is not known.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Australia, which emits 4 percent of the world's VAM, could theoretically create 96 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Australia would be $243 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $17 million.

References

Bray (1998): *The Appin and Tower Collieries Methane Energy Project*, a BHP Engineering Pty. Ltd. report provided by Geoff Bray, Project Engineer, September 26, 1998.

Mutmansky (2002): Personal dialog with Professor Emeritus Jan Mutmansky, Pennsylvania State University, January 17, 2002.

Saghafi (2002): E-mail communication with Abouna Saghafi, Commonwealth Scientific and Industrial Research Organisation, Sydney, New South Wales, Australia, September 16, 2002.

USEPA (2001): *Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990–2010,* US Environmental Protection Agency, EPA-430-R-01-007, December 2001.

Wendt et al. (2000): *Methane Capture and Utilisation Final Report*, Commonwealth Scientific and Industrial Research Organisation, Exploration and Mining Report #723R, Australian Coal Association Research Program (ACARP) Report #8058, May 2000.

VAM OXIDATION MARKET POTENTIAL: RUSSIA

Background

Russia's coal industry has undergone substantial restructuring to make it viable in a market economy. As elsewhere, unprofitable mines have been closed, and that process will continue. In addition, commercial privatization of the mines began in 1997 with the sale of state shares in two coal companies to Russian and other investors. As commercialization of potentially viable mines continues, market pressures will decree which mines remain operational and which close.

The largest and most important coal-producing region in Russia, the Kuzbass, located in the south-central part of the country, has hard coal reserves estimated to be on the order of 14.5 billion tonnes. USEPA (1996) reported that about one-third of the coal produced in Russia came from the Kuzbass. Other coal-producing regions in Russia that have the potential for CBM/CMM development are the Donetsk Basin, which Russia shares with Ukraine, and the Pechora Basin in the north.

Tailakov (2000a) states that 1998 underground coal production in Russia was approximately 80 million tonnes, with 19.4 percent of that total originating at gassy mines. He also quantified the percent of drained methane (not available to the ventilation system) at 30 percent. Thus, 70 percent of the methane liberated at gassy mines exits in the ventilation airflow. Tailakov (2000b) noted that the application of degasification in gassy Russian mines may increase in future years, along with coal production from underground mines. Russian mines sometimes employ bleeder shafts that emit VAM at high concentrations, and these may offer excellent opportunities for VAM projects.

Russia 2000 Data Summary		
UG Coal Production (MMT)		63.5
Unit VAM Release (m^3/tonne)		10.2
VAM Concentration (percent)		0.4*
Average Shaft Ventilation Airflow (m^3/sec.)		43*
VAM Emission:	MMT CO_2e	9.2
	Bm^3	0.6
Drained CMM Available (Mm^3/yr)		260

*Average

Business Climate

Russia has sufficient power production potential to supply domestic consumers and to export power to other countries. However, increased industrial demand for electricity also has forced power stations to operate at higher capacity, straining power companies' ability to procure fuel supplies. A lack of fuel supplies at power stations has already led to periodic power outages. Although Russia continues to struggle to establish a modern market economy, recent improvements in certain economic indicators and renewed governmental efforts to achieve needed reforms have combined to raise expectations of improved business investment opportunities in the country during the next decade. The real GDP growth rate in Russia was 8.3 percent in 2000 and 4.7 percent in 2001.

CBM and CMM development in Russia has been actively promoted and supported by the Russian Coalbed Methane Center, established in 1995 in Kemerovo. In June 2002 the Center attained the status of an independent, non-profit entity named the International Coal & Methane Center (ICMC) "Uglemetan" (www.uglemetan.ru). By continuing and building on the CBM Center's work, Uglemetan will focus its energies on disseminating information on CMM use in Russia, offering resource assessment and laboratory analytical services, conducting project feasibility and economic studies, facilitating CMM industry networking, developing and providing training, and offering other CMM development consulting and logistical services. Through prior USEPA-supported efforts of the CBM Center, Uglemetan can make available Russian coal permeability and desorption property data, providing a sound information base to support identification of CMM project opportunities. In addition, certain site-specific projects already have been proposed for implementation. Thus, the business climate for CMM development in Russia at this time is very supportive.

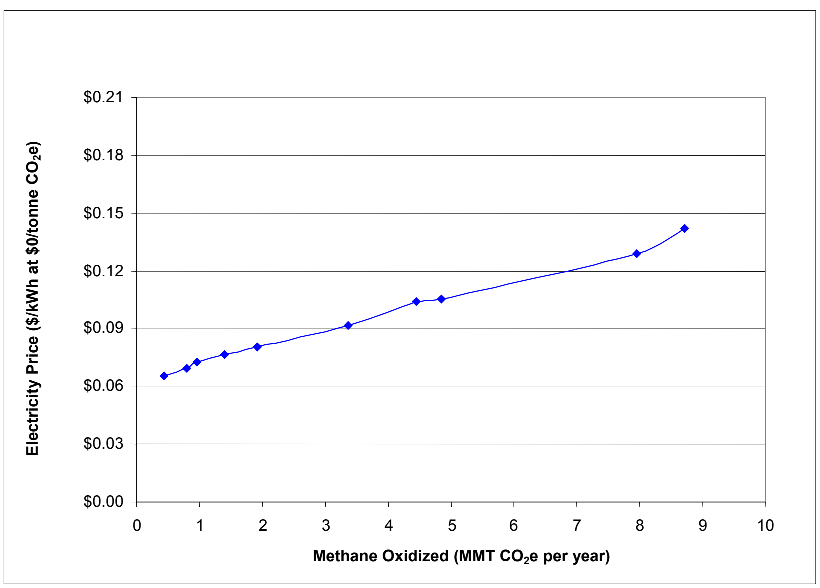

Figure A-13. MAC Analysis for Russia—Power Production

Methodology

Tailakov (2002a) provided underground, surface, and total coal production figures for 1990–2001. Tailakov (2002b) confirmed VAM concentration and ventilation airflow ranges and typical values previously provided, but clarified that the range values actually relate to regulatory limits rather than to in-field conditions. However, since the "typical" values provided very closely match the median concentration and flow values derived for the US from shaft-specific monitoring data, USEPA considered them to be adequate and appropriate for application in this analysis. Tailakov (2000a) provided total coal production projections for the years 2000, 2005, and 2010. These projections were adjusted to estimate underground coal production assuming that the proportion of underground coal production remains constant at 29 percent over the next two decades. Tailakov's coal production projections provided both minimum and maximum production estimates, and USEPA based its analysis on the minimum production values and interpolated and extrapolated from the 2000, 2005, and 2010 projections.

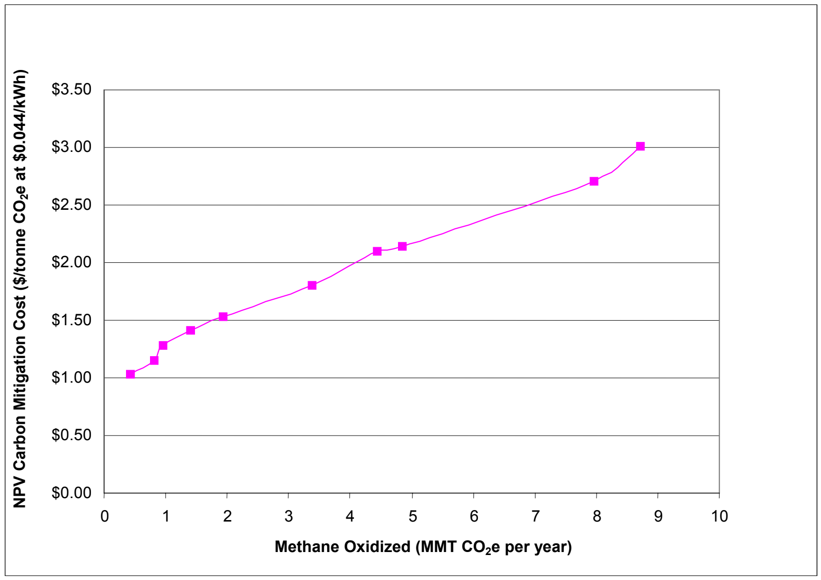

Figure A-14. MAC Analysis for Russia—Carbon Mitigation

The ratio of 1998 underground coal produced and methane released in gassy underground coal mine ventilation systems was used to predict ventilation air methane emissions through 2020. In 1998, 798.5 Mm^3 of methane were released in Russia from underground coal mine ventilation air systems. With underground coal production of 78.48 MMT that year, that emission equates with a unitized VAM release rate of 10.18 m^3 per tonne produced. Combining that value with the annual total coal production projections yielded annual VAM emissions estimates.

Data from USEPA (1996) quantifying CMM degasification and utilization in Russia in 1994 revealed that over 260 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Both US and Russian underground coal mines employ bleeder shafts to enhance degasification at longwall operations. Therefore, in constructing the MAC curve for Russia, the analysis applied the full US distribution of VAM concentration and ventilation airflow. Russian bleeder shaft management is different from that in the US, however. Brunner (2000) noted that Russian bleeder shafts are managed so that they drain methane at higher concentrations than is the case in the US, discharging that gas through explosion-proof fans at the surface. Tailakov (2002b) corroborated this practice and reported that the Russian bleeder shafts exhibit methane concentrations as high as 3–12 percent.

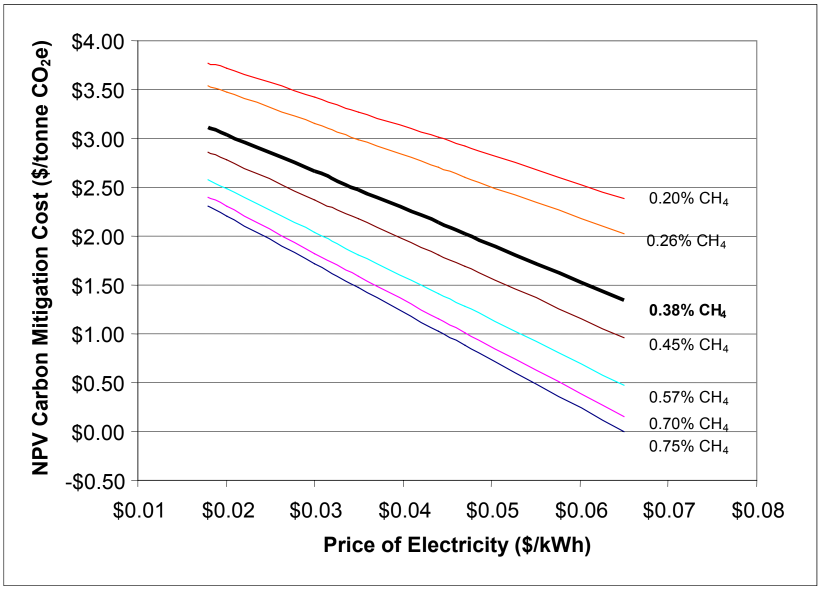

Figure A-15. Opportunity Costs for Russia

Uncertainties

- The possible increase in degasification at gassy Russian mines noted by Tailakov (2000b) may result in a reduction in the amount of methane exiting from mine ventilation systems per unit of coal produced, thus causing this analysis to overestimate the actual emissions. However, the possible increase in underground coal production also noted by Tailakov may offset the methane release reduction attributable to increased gas drainage. No basis for quantifying this relationship is available at this time.

- Projections of the likely trend in future underground versus surface coal production would improve the VAM emission analysis.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Russia, which emits almost 4 percent of the world's VAM, could theoretically create 141 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Russia would be $498 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to almost $56 million.

References

Brunner (2000): *Summary of Kuznetsk Coal Basin Mining Conditions and their Implications on Methane Emissions Reduction Projects*, trip report submitted to US Environmental Protection Agency, Coalbed Methane Outreach Program, March 28, 2000.

Tailakov (2000a): E-mail communication with Oleg Tailakov, Director, Russia Coalbed Methane Center, August 30, 2000.

Tailakov (2000b): E-mail communication with Oleg Tailakov, Director, Russia Coalbed Methane Center, Kemerovo, Russia, December 18, 2000.

Tailakov (2002a): Underground, surface, and total coal production data provided by Oleg Tailakov, Director, Russia Coalbed Methane Center, Kemerovo, Russia, July 11, 2002.

Tailakov (2002b): Personal dialog with Oleg Tailakov, Director, Russia Coalbed Methane Center, Kemerovo, Russia, December 19, 2002.

USEPA (1996): Reducing Methane Emissions from Coal Mines in Russia: A Handbook for Expanding Coalbed Methane Recovery and Use in the Kuznetsk Coal Basin, US Environmental Protection Agency, Office of Air and Radiation, EPA-430-D-95-001.

VAM Oxidation Market Potential: South Africa

Background

Because methane drainage is not currently employed in South Africa, essentially all of the methane liberated from gassy underground coal mines is released via mine ventilation systems at very low concentrations. Furthermore, although mining gassy anthracite coal will decline in South Africa, mining deeper bituminous coals will increase, so these factors will balance out, and the average ratio of methane released per tonne of coal mined underground should stay about the same through 2020 (Nundlall, 2001).

Annual underground coal production estimates for the period 2000–2005 were provided by Nundlall (2001), but that source did not supply projections from 2006 and beyond. An earlier reference (Lloyd et al., 2000), however, did project overall coal production for the period 1990–2030. That source predicted an approximate 7 percent rise in production from 2000 to 2007, followed by a drop to a level roughly 3 percent below 2000 levels by 2020. Thus, on average, underground coal production for the period 2000–2020 will approximate that exhibited in 2000.

Business Climate

Although South Africa's economic growth has been somewhat sluggish in recent years, its economy on the whole is strong. Thus, where technically feasible VAM development opportunities present themselves, business and economic factors in the country should be supportive of project development and implementation.

South Africa 2000 Data Summary

UG Coal Production (MMT)		142.1
Unit VAM Release (m^3/tonne)		2.8
VAM Concentration (percent)		0.1*
Average Shaft Ventilation Airflow (m^3/sec.)		N/A
VAM Emission:	MMT CO_2e	5.8
	Bm^3	0.4
Drained CMM Available (Mm^3/yr)		N/A

* Mean

Methodology

Based on the expected trend in underground coal production revealed in Lloyd et al. (2000), the annual underground coal production level reported by Nundlall (2001) for 2005 was assumed to approximate the average production level for the period 2006–2020.

Nundlall (2001) indicates that the typical ventilation airflow rates at South African mines are "extremely variable" and that VAM concentrations range from 0.05 percent to 0.2 percent. Thus, the higher end of the concentration range falls at the lower end of the current VAM oxidation technology capability range. Because of these very low VAM concentrations, South African mines were not viewed as attractive candidates for oxidation technologies at this time. This conclusion was confirmed by Lloyd (2002), who stated that the average depth of underground coal being mined in the country is only about 80 meters, and the coal therefore is often largely degassed. This condition is reflected in recent studies in such mines that have yielded measurements of methane in return airways of 0.08 percent, plus or minus 0.0002 percent.

Nundlall (2001) also provided data quantifying the rate of methane release per tonne of coal mined underground at 2.83 m^3 per tonne. That figure was applied to the estimates of annual underground coal projections to obtain annual estimates of VAM release throughout the study period.

Data to quantify drained CMM available for use as supplemental fuel for VAM oxidation projects in South Africa were unavailable.

Uncertainties

- Although typical VAM concentrations at South African coal mines are below levels considered necessary to support current VAM oxidation technologies, the percentage of mines with concentrations higher than the average, and thus potentially able to support oxidation projects, is not known. It is possible that viable project potential does exist at some mines in the country.

Market Potential

The study did not include a MAC curve for South Africa, which emits less than 3 percent of the world's VAM, because of low VAM concentrations.

References

Lloyd et al. (2000): P.J.D. Lloyd, D. van Wyk, A. Cook, and X. Provost, *SA Country Studies: Mitigating Options Project, Emissions from Coal Mining*, Final Report, June 2000.

Lloyd (2002): E-mail communication with P.J.D. Lloyd, Energy Research Institute, University of Cape Town, Cape Town, South Africa, September 10, 2002.

Nundlall (2001): E-mail communication with Vijay Nundlall, Senior Inspector of Mines, Occupational Hygiene, Pretoria, South Africa, September 24, 2001.

VAM Oxidation Market Potential: Poland

Background

In Poland hard coal is produced at underground mines and the vast majority (about 95 percent) of Poland's underground coal currently is produced in the Upper Silesian Coal Basin (USCB). Projections estimate that the basin will continue to supply over 90 percent of total production through the next two decades (World Coal, 2001a). USEPA (1995) reports that 28 percent of methane liberated is drained, 79 percent of which is utilized. Thus, 72 percent of methane liberated by underground mining exits through ventilation systems.

A government program enacted in 1998 and titled "Reform of the Hard Coal Industry in Poland in 1998–2002" is striving to rationalize the country's underground coal mining industry. That is being achieved by increasing the productivity and, hence, the economic viability of its domestic mining entities (World Coal, 2001b and 2001c). The country requires a stable, market economy-based underground coal industry, because it produces essentially all of its electric power from coal, and projections indicate that hard coal will remain the primary power production resource through the next two decades (World Coal, 2001a).

Business Climate

Poland has an expanding economy and is in the process of restructuring and reforming its energy industry. Its abundant reserves of coal provide a secure source of energy and foreign exchange, but heavy reliance on coal is also a major source of pollution. The Polish government expects electricity demand to grow by over 50 percent by 2020.

Poland 2000 Data Summary		
UG Coal Production (MMT)		102.1
Unit VAM Release (m^3/tonne)		3.9
VAM Concentration (percent)		0.3*
Average Shaft Ventilation Airflow (m^3/sec.)		221*
VAM Emission:	MMT CO_2e	5.7
	Bm^3	0.4
Drained CMM Available (Mm^3/yr)		45

*Weighted average

Grzybek (2001) reports that coalbed methane has been captured and productively used in Poland since 1952. Although CMM use declined sharply in 1993 when pipeline injection ceased, the increase in its use by the power sector has offset that decline. Furthermore, CMM use has diversified through its increased application in the chemical and oil refining industries. Thus, the value of CMM is recognized in Poland and conditions at present and into the future are good for implementing CMM projects.

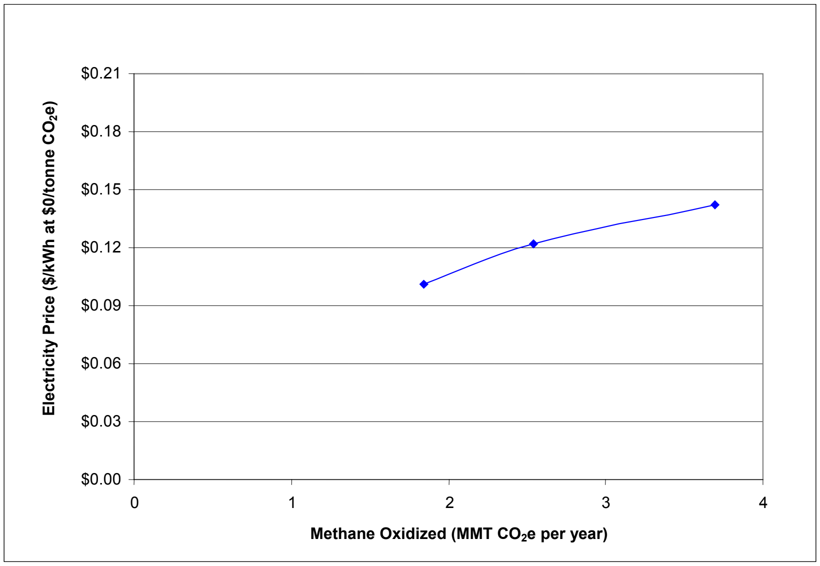

Figure A-16. MAC Analysis for Poland—Power Production

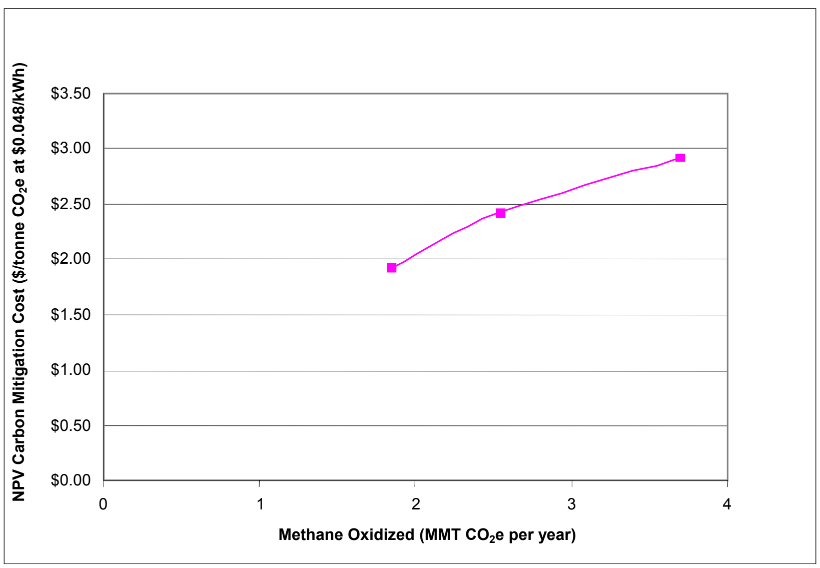

Figure A-17. MAC Analysis for Poland—Carbon Mitigation

The real GDP growth rate was 4 percent in 2000 and 2.5 percent in 2001.

Methodology

Kwarcinski (2000) provided VAM releases for 1991 to 1996 and hard coal production for 1995 to 2000, 2005, 2010, 2015, and 2020. Those data reveal a VAM emission rate of 3.91 m^3 per tonne of coal produced underground in Poland. Data in *World Coal* (2001a) confirmed the rate of decline in production levels reported by Kwarcinski. USEPA interpolated from the underground coal production data points to estimate future annual coal production for the 2000–2020 period. USEPA derived VAM emission projections for the study period by applying the VAM emission rate obtained from Kwarcinski to the projections of annual coal production.

Kwarcinski (2000) characterized the range of VAM concentration in Poland as 0.1–0.7 percent. Because USEPA has detailed, mine-specific VAM characterization data available for the subset of gassy mines in Poland, however, those data, which in 1993 reflected a VAM concentration range of 0.1–0.4 percent (USEPA, 1995), were used in this analysis. Thus, the market potential for Poland presented in this analysis underestimates the market if the more recent VAM concentration range estimate is correct. USEPA (1995) provides underground coal production statistics for 32 Polish mines, 16 of which also have VAM concentration and ventilation system airflow statistics reported. From those data, USEPA derived a weighted average VAM concentration (0.26 percent) and ventilation system airflow (221 m^3 per second) for the subset of mines that have VAM concentrations high enough to support oxidation projects. Data from USEPA (1995) quantifying CMM degasification and utilization in Poland in 1993 revealed that approximately 45 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

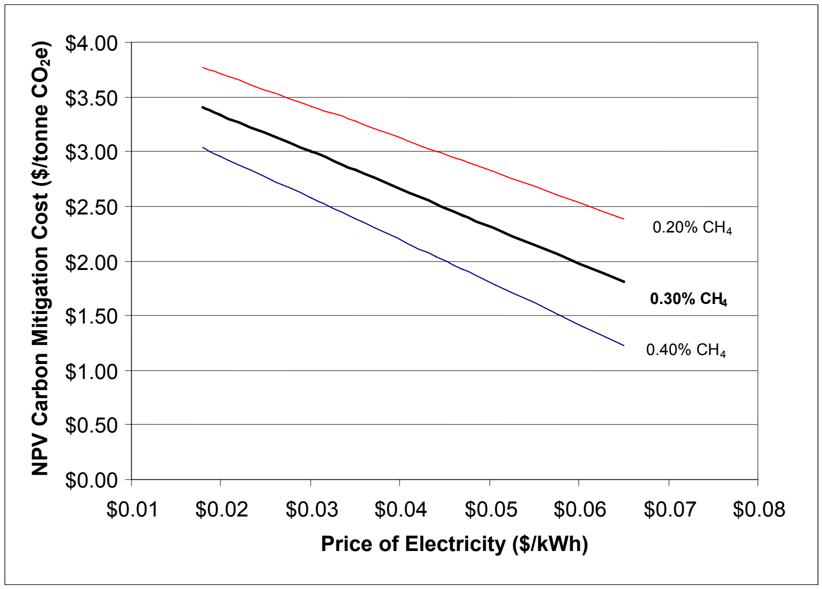

Figure A-18. Opportunity Costs for Poland

Uncertainties

- The extent to which the ventilation flow characterization data reported by USEPA (1995) reflect conditions at Polish mines at present is unknown.

Market Potential

In generating the MAC curves for Poland the total annual volume of VAM emitted by the country overall was reduced to reflect the fact that data in USEPA (1995) reveal that the mines in Poland that are gassy enough to offer viable VAM oxidation opportunities equate with 65 percent of all VAM released there. With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Poland, which emits over 2 percent of the world's VAM, theoretically could produce 52 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Poland would be $258 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $22 million.

References

Grzybek (2001): "Utilization of Coalbed Methane in Poland," I. Grzybek, in *Proceedings of the 4th International Symposium on Eastern Mediterranean Geology,* Isparta, Turkey, May 24-25, 2001.

Kwarcinski (2000): E-mail communication with Jan Kwarcinski, Polish Geological Institute, Upper Silesian Branch, September 2000.

USEPA (1995): *Reducing Methane Emissions from Coal Mines in Poland: A Handbook for Expanding Coalbed Methane Recovery and Utilization in the Upper Silesian Basin,* US Environmental Protection Agency, Office of Air and Radiation, EPA/430-R-95-003, April 1995.

World Coal (2001a): "Hard Coal in Poland: Changes and Prospects," *World Coal,* November 2001, Vol. 10, No. 11.

World Coal (2001b): "An Industry in Reform," *World Coal,* November 2001, Vol. 10, No. 11.

World Coal (2001c): "Fifty Years of Activity," *World Coal,* November 2001, Vol. 10, No. 11.

VAM OXIDATION MARKET POTENTIAL: KAZAKHSTAN

Background

As of 2000, most coal operations in Kazakhstan were privately owned. Through this privatization process, enhanced by legislative changes that have liberalized trade, the future of Kazakhstan's underground coal mines appears to be sound. (World Coal, 2000)

Business Climate

Kazakhstan is important to world energy markets because it has significant oil and natural gas reserves. As foreign investment pours into the country's oil and natural gas sectors, the landlocked Central Asian state is beginning to realize its enormous production potential. With sufficient export options, Kazakhstan could become one of the world's largest oil producers and exporters in the next decade.

Kazakhstan 2000 Data Summary

UG Coal Production (MMT)		8.2
Unit VAM Release (m^3/tonne)		38.3
VAM Concentration (percent)		0.3*
Average Shaft Ventilation Airflow (m^3/sec.)		186
VAM Emission:	MMT CO_2e	4.5
	Bm^3	0.3
Drained CMM Available (Mm^3/yr)		25

* Mean

Conditions for CMM project development in the country are sound, with the Kazakhstan Climate Change Coordination Center actively providing legal and other support for such initiatives. Broad-scale activities include approval of the Methane Center of Kazakhstan's work program and schedule of activities relating to greenhouse gas emission mitigation. Specific initiatives include improving the country's methane inventory (including methane emitted from underground coal mines), assessing CBM reserves, conducting degasification demonstration projects, analyzing the legislative and investment environment affecting and barriers faced by CMM project developers, training, and information transfer. Those efforts should substantially improve the body of information available to support effective project identification and planning.

Data from Republic State Enterprise (2002) quantifying CMM degasification and utilization in Kazakhstan in 2000 revealed that over 25 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

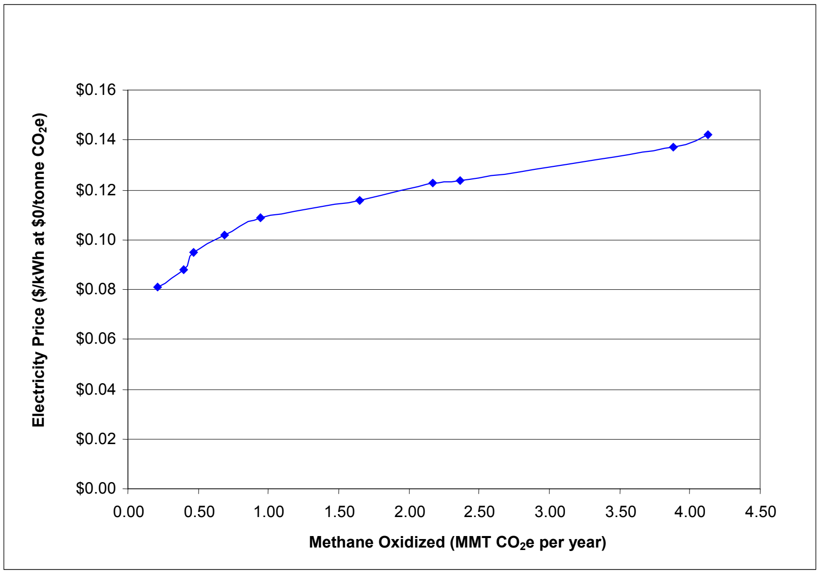

Figure A-19. MAC Analysis for Kazakhstan—Power Production

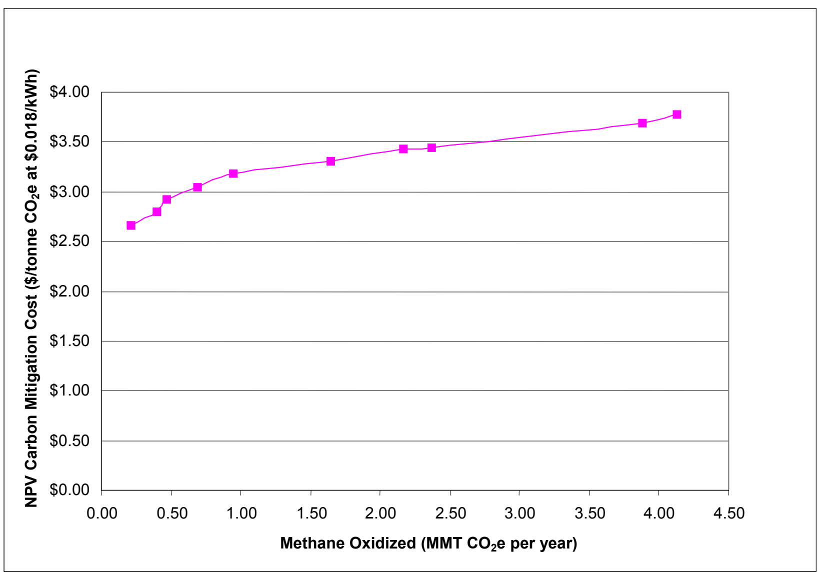

Figure A-20. MAC Analysis for Kazakhstan—Carbon Mitigation

Methodology

Shvetz (2001) reported a methane concentration range of 0.07–0.5 percent, with a mean of 0.29 percent for Ispat Karmet mines, Kazakhstan's largest underground coal company. He also stated that the volume of methane entering the atmosphere from Ispat Karmet underground coal mine ventilation systems in 2000 was 314 Mm^3 and that those mines produced 8.2 million tonnes. USEPA used those data to calculate a methane release rate of 38.3 m^3 per tonne of underground coal produced. Shvetz projected that annual production from Ispat Karmet underground mines in 2001 would be 8.5 million tonnes and for the period 2001–2005 would be 8.65 million tonnes per year. In the absence of additional information regarding future underground coal production, USEPA assumed that the production level for the 2001–2005 period also reflects that for the 2006-2020 period and interpolated and extrapolated from the given figures to obtain annual underground coal production estimates for the study period. Combining the VAM emission rate with annual underground coal production yielded estimates of annual VAM liberation.

Uncertainties

- The extent to which the Ispat Karmet mines are representative of the other underground coal mines in Kazakhstan is not known.

- The extent to which the underground coal production projection for the 2001–2005 period will represent actual production in the 20-year study period is unknown.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Kazakhstan, which emits almost 2 percent of the world's VAM, could theoretically create 11 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Kazakhstan would be $29 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to almost $2 million.

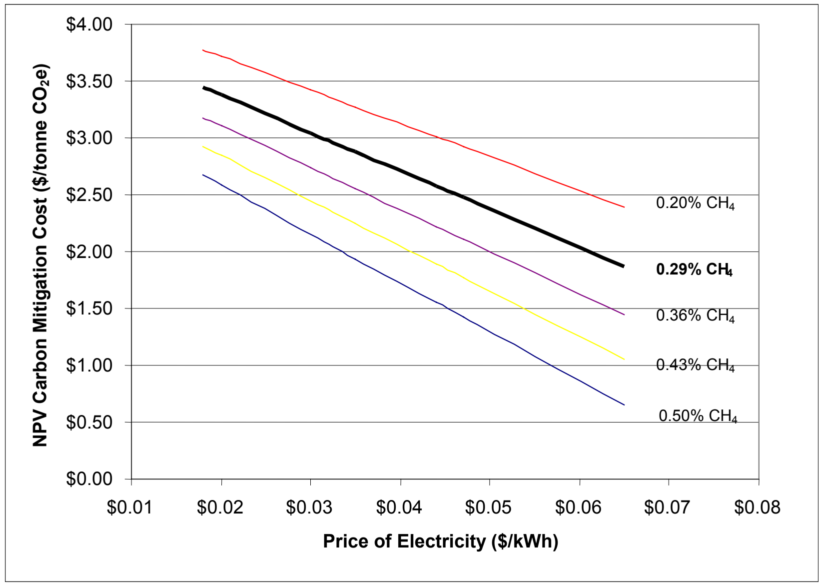

Figure A-21. Opportunity Costs for Kazakhstan

References

RSE (2002): *Kazakhstani GHG Emissions Inventory From Coal Mining and Road Transportation*, Republic State Enterprise, Kazhydromet, July 2002.

Shvetz (2001): E-mail communication with Igor A. Shvetz, Director, Ispat Karmet JSC, Karaganda, Kazakhstan, September 7, 2001.

World Coal (2000): "Industry in Motion," *World Coal,* February 2000, Volume 9, Number 2.

VAM OXIDATION MARKET POTENTIAL: INDIA

Background

In India, underground coal production currently comprises approximately 25 percent of total production, and annual tonnage of underground coal produced there has remained essentially steady over the past two decades (World Coal, 1999). Singh (2001a) observes India's trend toward a decrease in the share of underground coal production. That trend, however, appears to derive primarily from a dramatic increase in surface production in recent years rather than from a drop in absolute production from underground mines (World Coal, 1999). The coal seams currently being exploited are not particularly gassy, and methane concentrations in ventilation airflows even at the gassiest mines are low, typically below 0.3 percent. This is because underground coal mining in India is very labor intensive and high ventilation airflows are necessary to provide adequate air for the many miners working below ground. Also, less methane is released into the workings per unit time than is the case in highly mechanized mines such as those in the United States (Singh, 2002). Therefore, until deeper, gassier seams are tapped, India's potential for profitable VAM oxidation projects will remain modest at best. Singh (2001b) states that 66 percent of the underground mines emit less than 1 m^3 per tonne of coal produced, 27 percent of underground mines emit from 1 to 10 m^3 per tonne, and the remaining mines (7 percent) emit over 10 m^3.

India 2000 Data Summary

UG Coal Production (MMT)		69.1
Unit VAM Release (m^3/tonne)		4.0
VAM Concentration (percent)		0.1*
Average Shaft Ventilation Airflow (m^3/sec.)		40*
VAM Emission:	MMT CO_2e	4.0
	Bm^3	0.3
Drained CMM Available (Mm^3/yr)		N/A

* Typical

Business Climate

India, the world's sixth largest energy consumer, plans major energy infrastructure investments to keep up with increasing demand—particularly for electric power. India also is the world's third-largest producer of coal, and relies on coal for more than half of its total energy needs.

India is trying to expand electric power generation capacity, as current generation is seriously below peak demand. Although about 80 percent of the population has access to electricity, power outages are common, and the unreliability of electricity supplies is severe enough to constitute a constraint on the country's overall economic development. The government has targeted capacity increases of 107,000 MW by 2007. As of January

1999, total installed Indian power generating capacity was 103,445 MW, and it appears that the increase will fall short of expectations.

Methodology

For this analysis, Singh (2001a) provided estimates of underground coal production for 1999, 2006, and 2011; total VAM release for those years; VAM concentrations at gassiest mines (typically below 0.3 percent and often below 0.1 percent); and a typical ventilation airflow rate (i.e., 10–15 m^3 per second in small mines and 40 m^3 per second in larger mines). From the coal production and VAM release data, USEPA derived a value for unit methane release per tonne of coal produced of 4.02 m^3 per tonne. Also, USEPA interpolated and extrapolated from the three sets of coal production and VAM release data points to estimate future annual coal production and VAM release for the 2000–2020 study period.

Data to quantify drained CMM available for use as supplemental fuel for VAM oxidation projects in India were unavailable.

Uncertainties

- The schedule of exploitation of gassy, deep coal is unknown at this time. Such exploitation, however, is expected to result in gassier ventilation air streams thus offering the potential for future VAM project development.

Market Potential

The study did not prepare a MAC curve for India, which emits less than 2 percent of the world's VAM, because of low VAM concentrations.

References

Singh (2001a): E-mail communication with Umesh Prasad Singh, Deputy Chief Engineer, Coal India, Ltd., Calcutta, India, July 11, 2001.

Singh (2001b): *Indian Coalbed Methane Scenario*, paper presented by Umesh Prasad Singh, Deputy Chief Engineer, Coal India, Ltd., Proceedings of the 2001 International Coalbed Methane Symposium, Tuscaloosa, Alabama, May 14–18, 2001.

Singh (2002): E-mail communication with Umesh Prasad Singh, Deputy Chief Engineer, Coal India, Ltd., Calcutta, India, September 27, 2002.

World Coal (1999): "Indian Coal: The Future?" *World Coal,* April 1999, Volume 8, Number 4.

VAM OXIDATION MARKET POTENTIAL: UNITED KINGDOM

Background

UK underground coal production and consumption has been in decline for years. In 1999, underground mines accounted for 21 million tonnes, or 58.3 percent of overall coal production, down from its 80.2 percent contribution in 1990. More telling in terms of trends is the fact that from 1990 to 1999 surface coal production declined by slightly over 15 percent while underground production declined by more than 70 percent.

This decline in coal production partly results from a move away from coal-fired electricity generation, the UK's largest industrial sector consumer of coal, to newer, combined-cycle, gas turbine-based generation. Although initiatives have been introduced to stabilize the current underground coal industry and redress to some extent the social impacts of that industry's collapse, the growth in gas-fired generation in the UK and Europe continues. Although coal-fired generation accounted for about 65 percent of the UK's power production in 1990, projections suggest that it will fall to less than 20 percent by 2012 (World Coal, 2000).

Business Climate

Prospects for methane emission control projects appear bright. The government has established a budget of £150–£200 million ($247.9–$330.6 million)[17] over five years to support a greenhouse gas emission trading market. In that market, firms can bid in a competitive auction for £215 million ($355.3 million) of government incentive money in return for pledges to cut emissions. UK Coal recently bid successfully for £21 million ($34.6 million) in emissions reductions under that program that they will achieve by installing CMM-based electricity generation equipment at a number of their 13 deep mines.

UK 2000 Data Summary

UG Coal Production (MMT)		~25
Unit VAM Release (m^3/tonne)		12.2
VAM Concentration (percent)		N/A
Average Shaft Ventilation Airflow (m^3/sec.)		N/A
VAM Emission:	MMT CO_2e	2.2
	Bm^3	0.2
Drained CMM Available (Mm^3/yr)		80

[17] Currency conversion based on January 2003 rates (£1=$1.647).

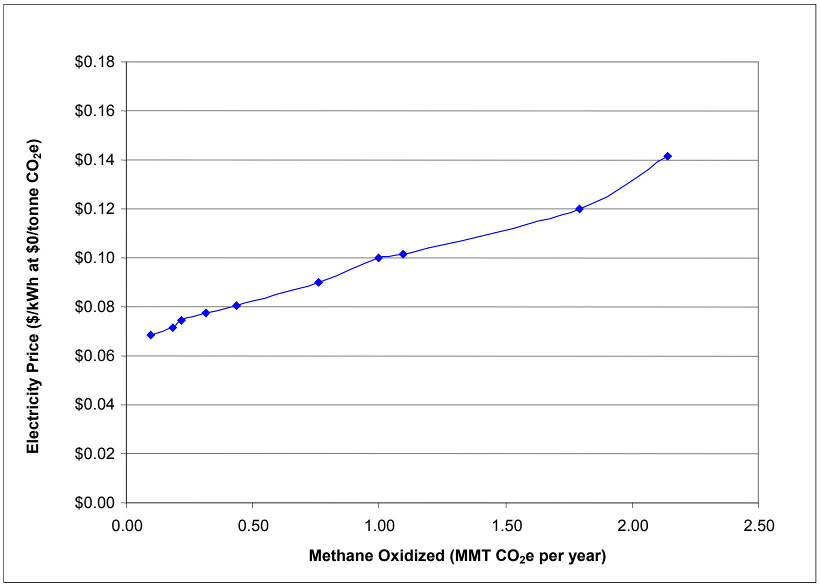

Figure A-22. MAC Analysis for the United Kingdom—Power Production

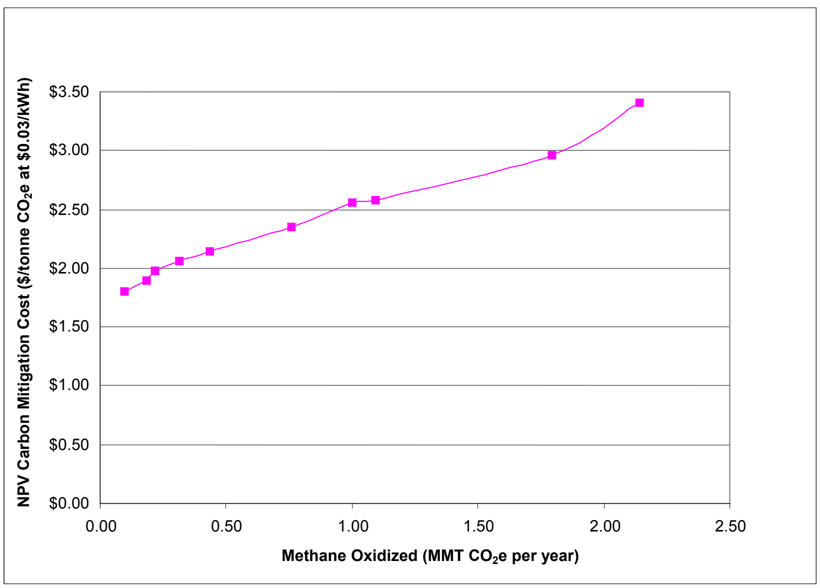

Figure A-23. MAC Analysis for the United Kingdom—Carbon Mitigation

Methodology

King (2002) reported ventilation shaft emissions and annual coal production for the 13 active underground mines owned by UK Coal, which constitute 90 percent of underground coal production in the country. From those data, a weighted average specific VAM emission of 12.2 m^3 per tonne was calculated. British Coal Technical Services (BCTS, ND) reported that atmospheric methane emissions data (i.e., emissions from ventilation and drainage systems) reviewed for their study of deep coal mines in the UK indicated that roughly 70 percent of those emissions originated at ventilation fan drifts.

Lacking data that projects future UK underground coal production, USEPA used the top-down methodology described earlier to estimate future VAM emissions. Analysts applied the underground coal production percentage reported by King (2002)—61 percent—to estimates of overall methane liberation from coal mining (in million tonnes of CO_2e) reported in USEPA (2001) for 2000, 2005, and 2010 to estimate that portion of methane emission attributable to underground mining. The analysis then applied the 70-percent VAM figure cited above to those values to disaggregate that portion of the projected overall underground methane emissions that would exit through mine ventilation systems.

Data from USEPA (2001) quantifying CMM degasification and utilization in the UK in 2000 revealed that over 80 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- The viability of underground mining in the UK is not clear, and therefore the availability of active underground mines to support VAM oxidation projects is uncertain.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in the United Kingdom, which emits less than 1 percent of the world's VAM, could theoretically create 31 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for the United Kingdom would be $96 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $8 million.

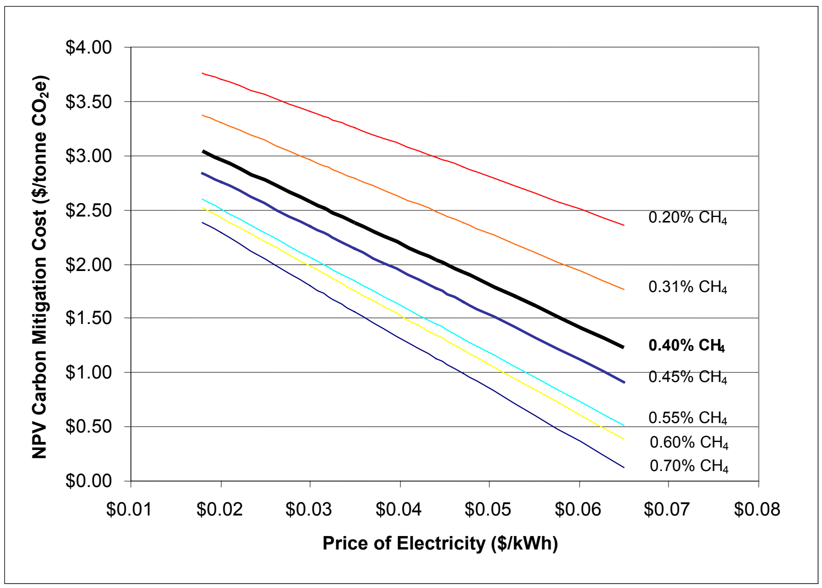

Figure A-24. Opportunity Costs for the United Kingdom

References

BCTS (ND): "Quantification of Methane Emissions from British Coal Mine Sources," *British Coal Technical Services and Research Executive,* report prepared for the Working Group on Methane Emissions, The Watt Committee on Energy.

King (2002): Data provided by Brian King, Senior Consultant, Neill and Gunter (Nova Scotia) Ltd., Dartmouth, Nova Scotia, Canada, December 8, 2002.

USEPA (2001): *Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990–2010,* US Environmental Protection Agency, EPA-430-R-01-007, December 2001.

World Coal (2000): "Prospects for UK Coal," *World Coal,* September 2000, Volume 9, Number 9.

VAM OXIDATION MARKET POTENTIAL: MEXICO

Background

USEPA had access to relevant data for the major gassy mines in Mexico, even though the country produces small amounts of coal. Santillan-Gonzalez (2001) provided overall coal production information and ventilation system methane liberation data for 2000, obtained for the five largest gassy underground coal mines in Mexico, which reflected a VAM emission rate of 28.4 m^3 per tonne. In addition, Santillan-Gonzalez (2001) also estimated 2000 coal production for one other gassy mine in the region.

Business Climate

Mexico's electricity sector is at a crossroads. Although generation has increased rapidly over the past decade, supply is not expected to meet demand growth over the next two decades. Given current grid capacity constraints, shortages could result. Failure to make substantial investments in generation capacity and infrastructure could adversely affect the international competitiveness of key northern industrial regions. Although about 95 percent of Mexican households currently are electrified, there are still many thousands of rural towns without electricity. It is reported that consumption growth over the next five years will be 45 percent.

Mexico 2000 Data Summary

UG Coal Production (MMT)		4.8
Unit VAM Release (m^3/tonne)		28.4
VAM Concentration (percent)		0.5*
Average Shaft Ventilation Airflow (m^3/sec.)		140*
VAM Emission:	MMT CO_2e	1.9
	Bm^3	0.1
Drained CMM Available (Mm^3/yr)		N/A

* Average

Methodology

Santillan-Gonzalez (2001 and 2002) observed that the eight mines he represents are the only underground coal mines in Mexico likely to support VAM projects and reported VAM characterization and coal production for those mines for 2000 and 2002–2012. His data reveal a VAM concentration range of 0.4–0.8 percent, with an average of 0.5 percent, and a ventilation airflow range of from 91 m^3 per second to 197 m^3 per second, with an average value of 140 m^3 per second. USEPA interpolated from the reported coal production data to obtain an estimate for 2001. Because production estimates were relatively constant for 2008–2012, USEPA assumed that the value reported for 2012 (5.0 million tonnes) will be representative

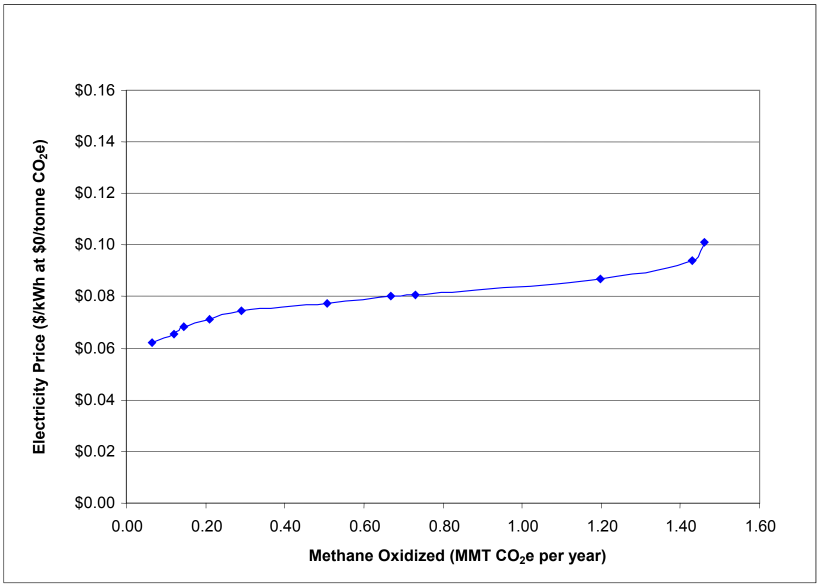

Figure A-25. MAC Analysis for Mexico—Power Production

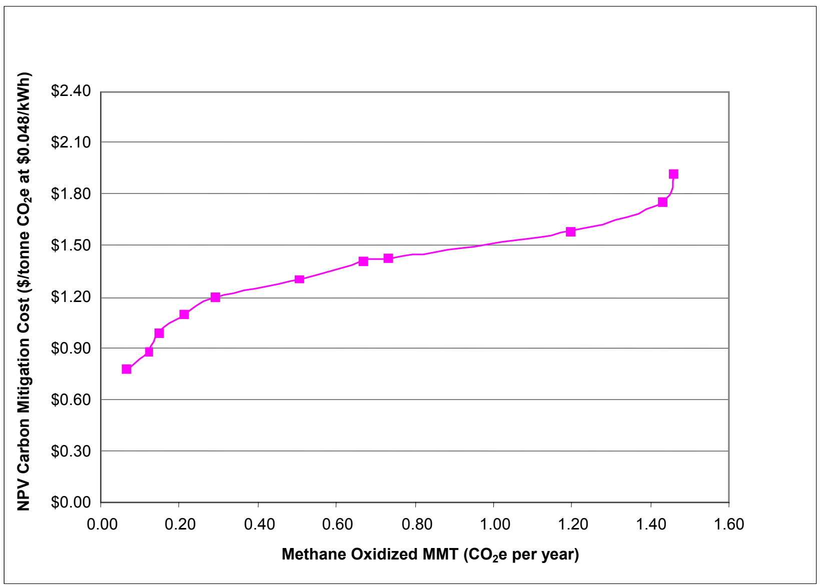

Figure A-26. MAC Analysis for Mexico—Carbon Mitigation

of the period 2013–2020. Santillan-Gonzalez's projections indicate that coal production at three of the eight mines will have been completed by 2008. Thus, the other five mines represent prospects for long-term VAM projects in Mexico. Combining the VAM unit emission value (28.4 m^3 per tonne) with the projected annual coal production estimates provided a basis for projecting annual VAM emissions from 2000 to 2020. Data to quantify drained CMM available as supplemental fuel for VAM oxidation projects in Mexico were unavailable.

Uncertainties

- If available, annual coal production projections for the study period could be used with the data quantifying methane emissions per unit of coal produced underground provided by Santillan-Gonzalez (2001) to refine the annual VAM emission estimated.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Mexico, which emits less than 1 percent of the world's VAM, could theoretically create 27 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for

Mexico would be $62 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $11 million.

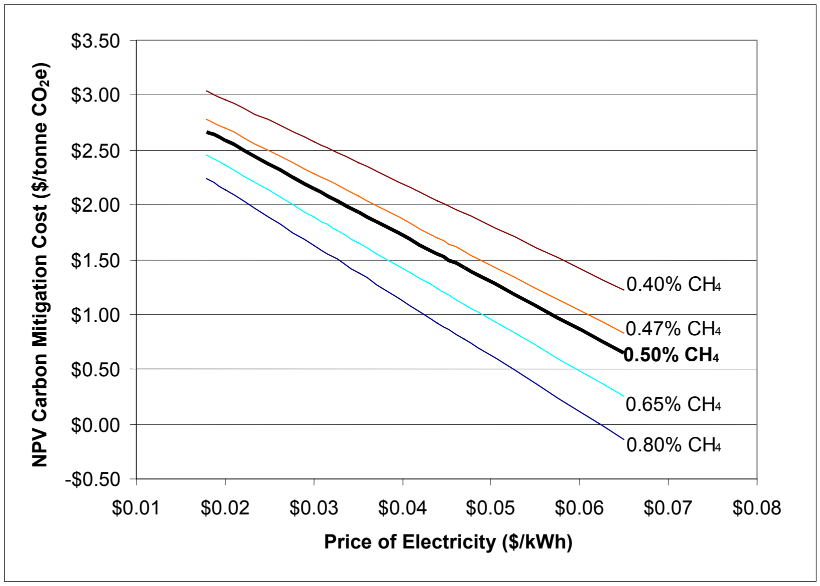

Figure A-27. Opportunity Costs for Mexico

References

Santillan-Gonzalez (2001): E-mail communication with Mario Alberto Santillan-Gonzalez, Mining Engineer, Minerales Monclova S.A. de C.V., Palau, Coahuila, Mexico, July 19, 2001.

Santillan-Gonzalez (2002): E-mail communication with Mario Alberto Santillan-Gonzalez, Mining Engineer, Minerales Monclova S.A. de C.V., Palau, Coahuila, Mexico, September 21 and 25, 2001.

VAM OXIDATION MARKET POTENTIAL: GERMANY

Background

Current expectations anticipate a fairly stable demand for hard coal in Germany over the next two decades (World Coal, 1999). However, probable mine closures will result in decreased underground coal production. Although 10–12 collieries are expected still to be operating in the country by 2005, annual hard coal production will have fallen 40 percent below 1996 levels by that time. In Germany all hard coal is produced from underground mines, but at present none of those mines are employing bleeder shafts.

Radgen (2000 and 2002) reports that 61 percent of methane liberated in underground mining in Germany is released in the ventilation system, while 39 percent is drained (69 percent of which is used and 31 percent of which is vented to the atmosphere). Recent government incentives for environmentally sound, alternative power production (which includes that produced from coal mine methane) may result in accelerated utilization of CMM available from drainage systems as well as that in ventilation air (see below).

Germany 2000 Data Summary

UG Coal Production (MMT)		31.7
Unit VAM Release (m^3/tonne)		2.8
VAM Concentration (percent)		0.3*
Average Shaft Ventilation Airflow (m^3/sec.)		N/A
VAM Emission:	MMT CO_2e	1.2
	Bm^3	0.09
Drained CMM Available (Mm^3/yr)		80

* Average

Business Climate

Germany is one of the world's largest energy consumers. Because it has limited indigenous energy resources (except for coal), Germany is heavily import-reliant to meet its energy needs.

The German government has announced plans to at least double the contribution of renewable energy technologies in the country's overall electricity production technology mix by 2010, raising it from its current level of 5 percent to 10 percent (World Coal, 2000). As methane from coal mines is included in the mix of alternative fuels that are the focus of that transition, more aggressive methane drainage might be employed in the coming years. Specifically, in 2000, the government enacted legislation designed to provide for environmental protection while increasing the country's energy supply reliability. The act considers coal mine methane to be a renewable resource and provides for

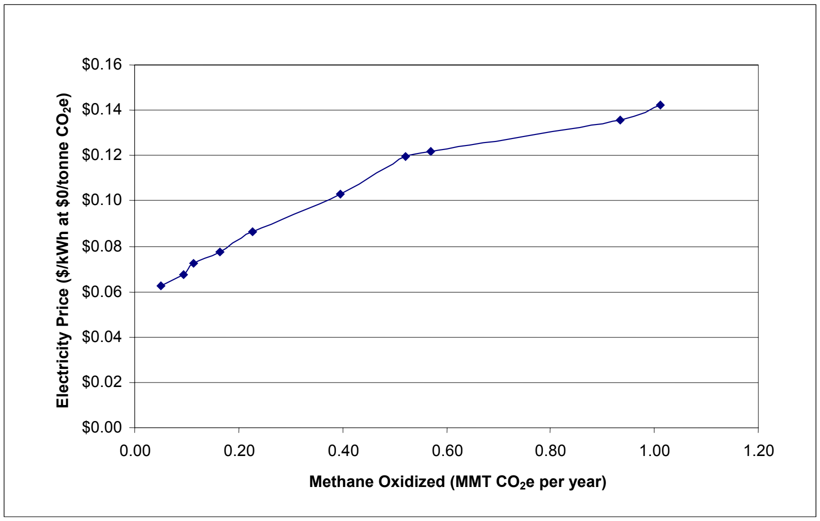

Figure A-28. MAC Analysis for Germany—Power Production

compensation in the amount of 0.0767 euros (US$0.07)[18] per kWh to be paid for electricity from installations with a generation capacity of under 500 kW using renewable resources and 0.0665 euros (US$0.06) per kWh for electricity from such installations with a capacity of over 500 kW (Radgen 2002).

Methodology

Underground coal production data for 2000, 2001, 2005, and 2010 were obtained from *World Coal* (2000, 2001a, and 2001b) and Radgen (2001a and 2002). Radgen (2001b) also supplied a specific methane liberation rate of 3–12 m^3 per tonne of coal produced underground, at an average of 4–5 m^3. Adjusting that average by applying the 61 percent figure reported for ventilation system methane releases yielded an average VAM release rate of 2.75 m^3 per tonne of underground coal. In an earlier communication, Radgen (2000) noted that, by law, ventilation air methane concentrations must fall below 1 percent and reported a VAM concentration range of 0.08–0.8 percent, with an average value being approximately 0.3 percent.

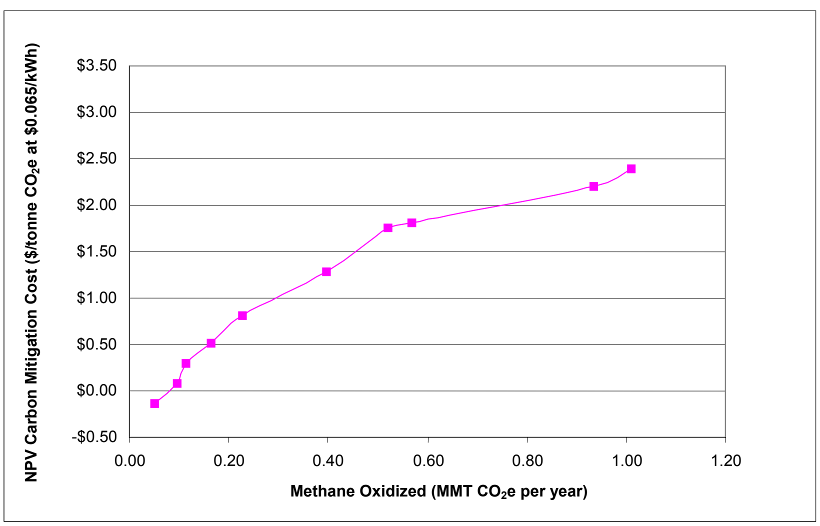

Figure A-29. MAC Analysis for Germany—Carbon Mitigation

USEPA interpolated from the underground coal production data points to estimate future annual coal production for the 2000–2010 period. Specific underground coal production data for the post-2010 period were unavailable. World Coal (1999) reports that a substantial decrease in production is ex-

[18] Currency conversion based on November 2002 rates.

pected to be evidenced by 2010 but that the German government does intend to maintain some level of production for energy security reasons. Thus, the analysis assumed that the annual production will remain constant at the 2010 level from 2011 through 2020. Combining the average methane release rate with annual underground coal production estimates yielded annual VAM release estimates for the 20-year study period.

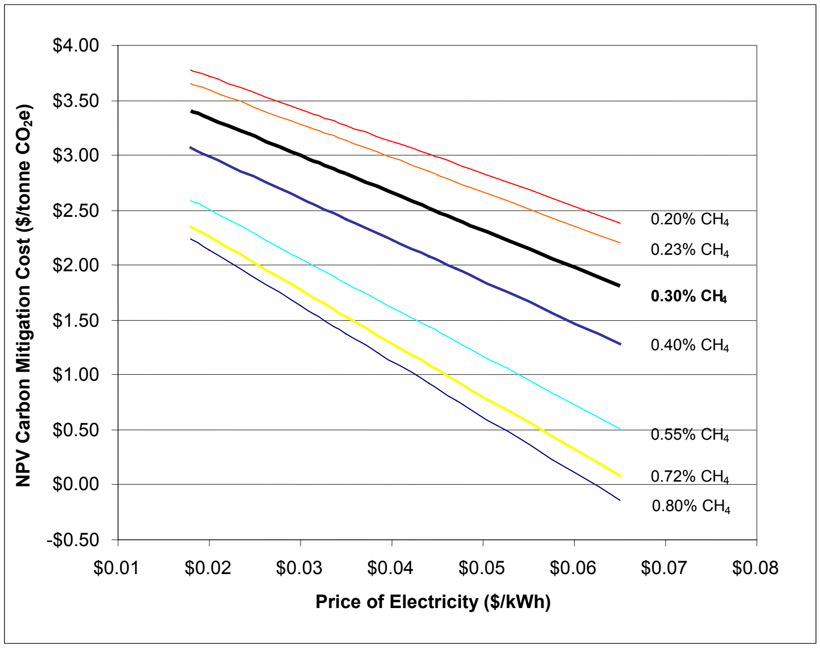

Figure A-30. Opportunity Costs for Germany

Data from Radgen (2002) quantifying CMM degasification and utilization in Germany in 2000 revealed that 80 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- An increase in the extent to which coal mine methane is captured and used from both active and abandoned mines may also result in a decrease in the volume of methane released to the ventilation system per unit of coal produced.

Market Potential

With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in Germany, which emits less than 1 percent of the world's VAM, could theoretically create 16 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for Germany would be over $63 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $9 million.

References

Radgen (2000): E-mail communication with Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany, August 28, 2000.

Radgen (2001a): E-mail communication with Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany, September 1, 2001.

Radgen (2001b): E-mail communication with Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany, December 31, 2001.

Radgen (2002): E-mail communication with Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany, October 15, 2002.

World Coal (1999): "Facing the Future," *World Coal,* February 1999, Volume 8, Number 2.

World Coal (2000): "Coal Industry and Energy Supply in Germany," *World Coal,* October 2000, Volume 9, Number 10.

World Coal (2001a): "Outlook for German Coal," *World Coal,* September 2001, Vol. 10, No. 9.

World Coal (2001b): "Life After Coal: Regeneration or Decline?," *World Coal,* September 2001, Vol. 10, No. 10.

VAM OXIDATION MARKET POTENTIAL: CZECH REPUBLIC

Background

The majority of coal produced in the Czech Republic is lignite produced from surface mines; all hard coal produced in the country is mined underground. Although once a major element of the Czech Republic's economy, domestic coal production has declined due to a variety of environmental and economic factors. Transition from coal-fired to natural gas-fired electric generation, competition from cheaper imported coal, and similar factors have driven that trend, which is expected to continue. As a result, projected VAM emissions also are expected to decline nationwide during the 2000–2020 study period.

Czech Republic 2000 Data Summary		
UG Coal Production (MMT)		14.9
Unit VAM Release (m^3/tonne)		3.9
VAM Concentration (percent)		0.3*
Average Shaft Ventilation Airflow (m^3/sec.)		221*
VAM Emission:	MMT CO_2e	0.8
	Bm^3	0.06
Drained CMM Available (Mm^3/yr)		10

Business Climate

The Czech Republic moved into positive economic growth in 2000 following three years of recession. Both electricity generation and consumption generally have been rising. The country is a net exporter of electricity.

Methodology

USEPA (1992) reported that in 1990 in the Ostrava-Karvina District, which produces 90 percent of the Czech Republic's coal, 73 percent of methane liberated from coal mining was emitted to the atmosphere from underground coal mine ventilation systems. Gavor (2002) reported coal production levels for 2000 and 2001 and also provided a production projection for 2020. USEPA extrapolated from those data to obtain production estimates for the intervening years. Mutmansky (2002) and USEPA (1992) note that the Czech Republic shares the Silesian coal basin with Poland and conditions are virtually the same on both sides of the border. Thus, for this analysis USEPA assumed that mining methods and VAM characteristics (i.e., weighted average VAM concentration of 0.259 percent and ventilation airflow of 221 m^3 per second) are similar to those in Poland as well. The VAM specific emissions value obtained for Poland (i.e., 3.91 m^3 per tonne of underground coal) was applied to the underground coal production projections to obtain VAM emission estimates for the study period.

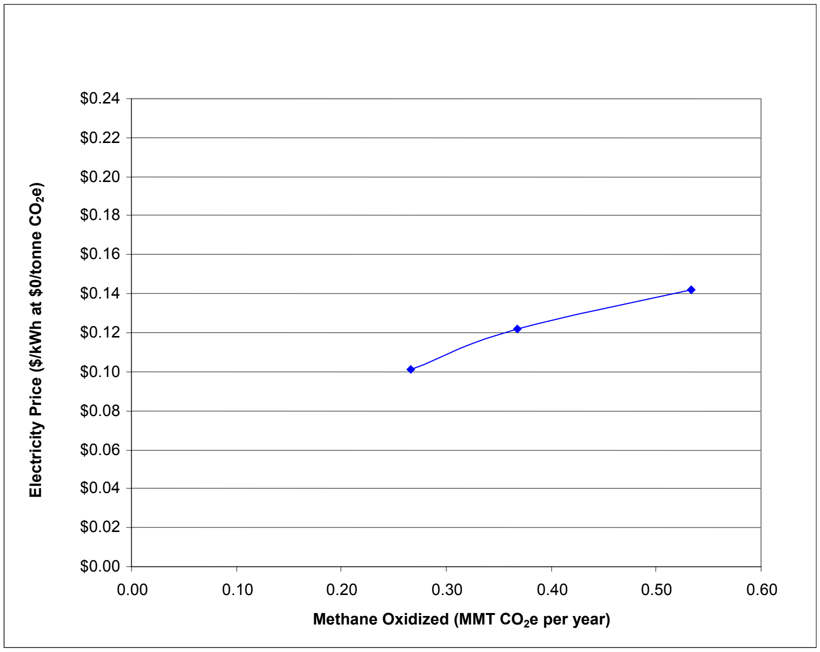

Figure A-31. MAC Analysis for the Czech Republic—Power Production

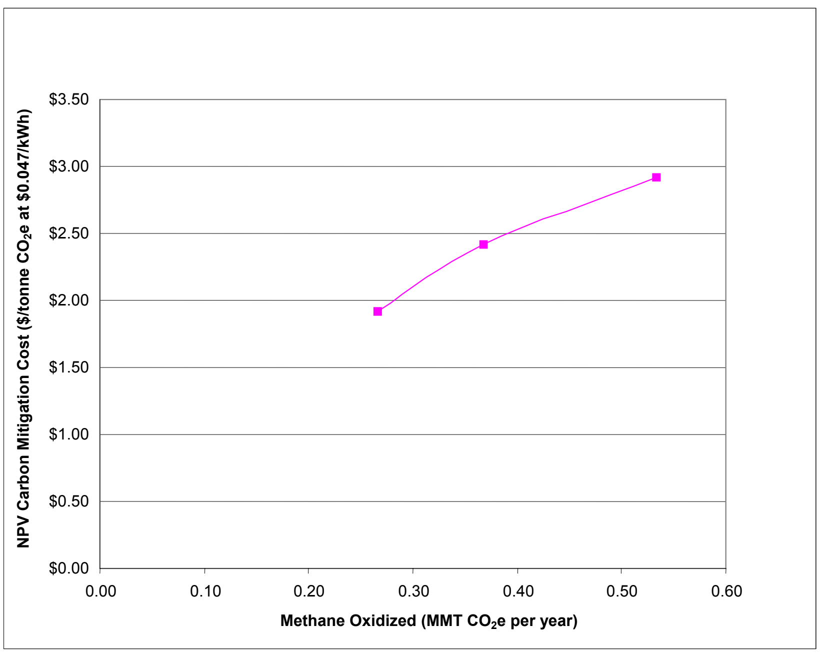

Figure A-32. MAC Analysis for the Czech Republic—Carbon Mitigation

Data from USEPA (2001) quantifying CMM degasification and utilization in the Czech Republic in 2000 revealed that over 10 Mm^3 of drained CMM per year is vented to the atmosphere and could be available for use as supplemental fuel for VAM oxidation projects.

Uncertainties

- The extent to which the ventilation system emissions reported by USEPA 1992 for the Ostrava-Karvina District reflect current or future VAM emissions is not known.

Market Potential

As was done for Poland, in generating the MAC curves for the Czech Republic, where mining conditions are similar to those in Poland, the total annual volume of VAM emitted by the country overall was reduced to reflect the fact that data in USEPA (1995) reveal that the mines in Poland (and by extension in the Czech Republic which shares the Silesian coal basin with Poland) that are gassy enough to offer viable VAM oxidation opportunities equate with 65 percent of all VAM released there. With methane abatement costs at $3.00 per tonne of CO_2e, VAM-derived power projects in the Czech Republic, which emits less than 1 percent of the world's VAM, could theoretically create 5 MW of net useable capacity. If the equipment value for each project were rounded to $10 million, the total equipment market estimate for the Czech Republic would be $54 million. Finally, the annual revenues that could accrue from such power sales in the country could amount to over $2 million.

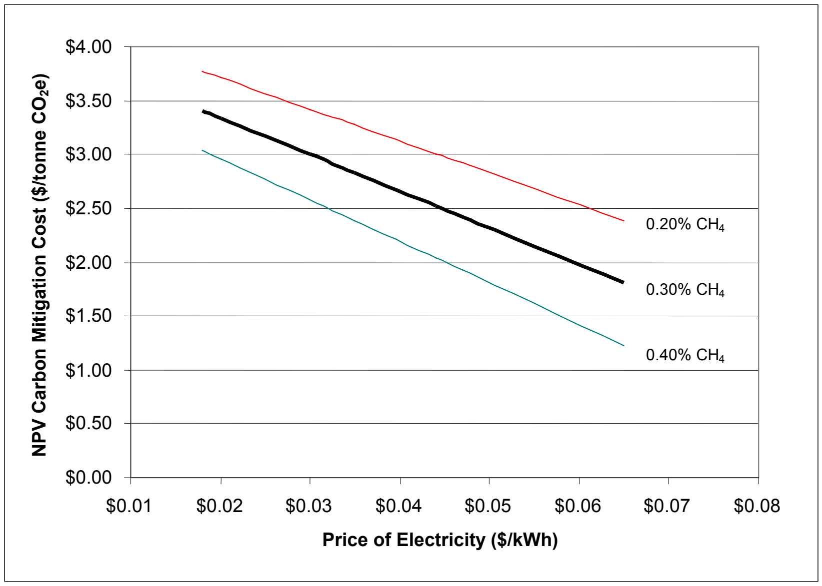

Figure A-33. Opportunity Costs for the Czech Republic

References

Gavor (2002): E-mail communication with Dr. Jiri Gavor, Partner, ENA Ltd., Prague, Czech Republic, November 6, 2002.

Mutmansky (2002): Personal dialog with Professor Emeritus Jan Mutmansky, Pennsylvania State University, January 17, 2002.

USEPA (1992): *Assessment of Potential for Economic Development and Utilization of Coalbed Methane in Czechoslovakia,* US Environmental Protection Agency, Office of Air and Radiation, EPA-430-R-92-1008, October 1992.

USEPA (2001): *Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990–2010,* US Environmental Protection Agency, EPA-430-R-01-007, December 2001.

APPENDIX B
SAMPLE CALCULATIONS

Illustrative Bottom-up Annual VAM Emission Calculation: China

Given:

- VAM specific emission rate = 6.8 m^3 methane/tonne coal
- 2000 underground coal production = 949.05x10^6 tonnes

Then:

- 6.8 m^3 VAM/tonne coal x 949.05x10^6 tonnes mined = 6.45 Bm^3 or 92.29 MMT CO_2e

Illustrative Top-down Annual VAM Emission Calculation: United Kingdom

Given:

- 2000 overall coal mining methane emissions = 5.2 MMT CO_2e
- In 1999 underground mines accounted for 61 percent of overall coal production
- 70 percent of those emissions originated at ventilation fan drifts

Then:

- 2000 overall coal mining methane emissions x 61% = 2000 emissions from underground mines:

  5.2 MMT CO_2e x 0.61 = 3.17 MMT CO_2e

- 2000 emissions from underground mines x 0.7 = 2000 VAM emissions:

  3.17 MMT CO_2e x 0.7 = 2.2 MMT CO_2e

Illustrative Non-US MAC Curve Development: China

Refer to the spreadsheet that follows the analytical steps described below in text to find the results of each step.

The method for creating a new VAM emissions distribution curve for each country used the data shown in Appendix A and proceeded as follows:[19]

1. The distribution of US VAM mitigated was ranked and the median concentration was identified (0.39 percent).

2. The cumulative distribution of annual US VAM flow (by concentration) was converted to a percentage distribution.

3. The mid-point of each country's concentrations was identified.

4. The shape of the VAM distribution curve that plots oxidized methane (in tonnes of CO_2e) against methane concentration needs to be created for each country. This was accomplished by fitting (using interpolation) the top half of the US curve to each country's top range (i.e., the interval between the median and the highest concentration). This involved calculating a decimal fraction (factor) representing each increment in the US tonnage-concentration curve (e.g., a 0.1 percent increment between 0.9 and 0.8 percent) divided by the US mid-point-to-top interval. The US distribution has a span of 0.61 percent from the median of 0.39 percent to the highest concentration grouping of 1.0 percent, and each increment down to 0.4 percent represents about 0.164 of that range. Steps 5 and 6 apply that factor to the top half of each country's range to distribute the tonnage-concentration points.

5. The top of each country's concentration range and the difference between that percentage and the median selected in Step 3 were identified. For example, the reported range from China's high of 0.75 percent to its "average" of 0.46 percent spans an interval of 0.3 percent.

6. A new concentration range (above the median only) was constructed using the factors developed in Step 4 and the range identified in Step 5. For the Chinese case, the factor of 0.164 multiplied by 0.3 percent—about 0.05 percent—becomes the concentration interval associated with each increment of the US tonnage distribution (see Step 8).

7. To distribute the bottom half of the curve from the mid-point to the lower end of a country's range, Steps 4, 5, and 6 were repeated.

[19] A separate calculation was necessary for concentrations above and below the median because reported patterns of mid-points and ranges are not consistent with each other or with the US pattern.

8. The new concentration range was matched with the NPV cost per tonne of CO_2e by interpolating the US concentration/cost relationships.

9. The new concentration range for each country was matched to the US distribution, as converted to percentages in Step 1.

10. That new concentration percentage distribution was multiplied by the tonnes of VAM (expressed as tonnes of CO_2e) that are emitted by each country.

11. The two series resulting from Steps 8 and 10 become the bases for each country's MAC curves.

CHINA MAC Curve: Calculation Steps

		US Values				China Values				
		VAM conc % group	*factor*	*cumulative CO2 % of total*	*cost NPV $/t CO2*	*VAM conc % group*	*approx distribut'n CO2 %*	*approx distribut'n CO2 mmt/y*	*adj NPV cost $/t CO2*	*electric price **$/kWh***
Step 3										
Mid point concentration = 0.45%										
Step 5	**>>**	1.00		4.48%	$0.73	**0.750**	4.48%	4.30	**$1.23**	$0.07
		0.90	0.163	8.36%	$0.93	0.701	8.36%	8.03	$1.33	$0.07
	>>	0.80	0.163	9.94%	$1.13	0.652	9.94%	9.55	$1.42	$0.07
Step 4	**>>**	0.70	0.163	14.48%	$1.33	0.603	14.48%	13.90	$1.52	$0.07
	>>	0.60	0.163	19.87%	$1.52	0.554	19.87%	19.08	$1.62	$0.08
		0.50	0.163	34.76%	$1.72	0.505	34.76%	33.37	$1.73	$0.08
		0.40	0.163	45.74%	$2.19	0.456	45.74%	43.92	$1.93	$0.09
Step 1	**>>**	**0.388**	0.020	**50.00%**	**$2.25**	**0.450**	50.00%	48.01	**$1.957**	$0.09
		0.30	0.306	71.33%	$2.66	0.313	71.33%	68.49	**$2.60**	$0.12
		0.25	0.174	84.86%	$2.89	0.234	84.86%	81.48	**$2.96**	$0.14
		0.20	0.174	98.02%	$3.13	0.156	98.02%	94.12		
		0.10	0.347	100.00%		**0.000**	100.00%	**96.02**		
				^^ *step 2*		**^^ *steps 6&7***	**^^ *step 9***	**^^ *step 10***	**^^ *step 8***	

APPENDIX C
BASIS FOR POWER PRICE USED IN THE ANALYSES

Selection of a Realistic Power Price

A VAM project with electricity-generation capability will need a substantial and predictable revenue stream from power sales to be credible with potential sources of financial support. USEPA estimated that a contract covering the anticipated plant output for five to seven years would be sufficient to satisfy the debt suppliers (i.e., repay their investment), since short contracts and spot pricing thereafter will likely pose little downside risk. Moreover, the outstanding principal on major project loans should be insignificant by that time, or secured by another asset, or both. The following discussion addresses the issues involved in predicting what prices might be available to a VAM project in the US for the purposes of executing a MAC analysis.

In the attempt to gather realistic cost estimates for this evaluation, USEPA posed the following two scenarios for consideration by persons active in the electric utility industry:

1. Export the power to the grid (either directly to the local utility or indirectly through a third party), or

2. Self-generate electricity so that the mine would save on power purchases and pass the savings along to the project entity.

Selecting a power price for the US analysis was a challenge because events that affect supply and demand in the electricity supply business are changing rapidly and are causing different effects in different areas of the country.

In view of the findings from this preliminary research effort for both exported and self-generated power, USEPA decided to assume an arbitrary average price of $0.03 per kWh for US projects. The $0.03 price reflects anecdotal reports of current pricing in the deep coal-mining regions of the US Rockies and Appalachia.

Non-US Power Prices

Where possible USEPA obtained estimates of representative industrial power pricing for other countries through direct contact with in-country coal industry experts. For countries where estimates were unavailable through direct contact, USEPA used power price data published by the International Energy Agency.

Power Price Summary

The following table lists the country-specific electric power prices employed in this analysis, and identifies the sources from which those prices were obtained.

Country	Rate (US$ per kWh)	Source
Australia	0.02	Shi Su, CSIRO Exploration and Mining, Kenmore, Queensland, Australia
China	0.035	Liu Wenge, Project Manager, China Coalbed Methane Clearinghouse, Beijing, China
Czech Republic	0.0468	International Energy Agency, World Electric Prices, IEA 2002
Germany	0.065	Dr. Peter Radgen, Project Manager, Fraunhofer ISI, Karlsruhe, Germany
India	0.07	Umesh Prasad Singh, Deputy Chief Engineer, Coal India, Ltd., Calcutta, India
Kazakhstan	0.018	International Energy Agency, World Electric Prices, IEA 2002
Mexico	0.0475	International Energy Agency, World Electric Prices, IEA 2002
Poland	0.0476	International Energy Agency, World Electric Prices, IEA 2002
Russia	0.044	International Energy Agency, World Electric Prices, IEA 2002
South Africa	0.01	P.J.D. Lloyd, Energy Research Institute, University of Cape Town, South Africa
United Kingdom	0.03	Phillip O'Quigley, Energy Finance Limited, Dublin, Ireland
Ukraine	0.03	Alexander Filippov, Programs Coordinator, Partnership for Energy and Environmental Reform, Kiev, Ukraine
United States	0.03	Richard Winschel, CONSOL Energy, South Park, Pennsylvania, USA; Patrick Reinks, Ingersoll-Rand Company - Energy Systems, Davidson, North Carolina, USA

APPENDIX D
TECHNOLOGY DEVELOPER/VENDOR CONTACT INFORMATION

Thermal Oxidizer

MEGTEC Systems

830 Prosper Road
P.O. Box 5030
De Pere, Wisconsin 54115-5030
United States

Contact:

Kenneth P. Zak
Director, Marketing and Business Development

Phone: (920) 339-2797
Fax: (920) 339-2784
E-mail: kzak@megtec.com

Catalytic Oxidizer

Neill and Gunter (Nova Scotia) Ltd.

130 Eileen Stubbs Avenue
Suite 1 South
Dartmouth, NSB3B2C4, Canada

Contact:

Brian King
Senior Consultant

Phone: (902) 434-7331
Fax: (902) 462-1660
E-mail: bking@ngns.com

Lean-Fuel Microturbine

Ingersol-Rand Energy Systems

800-D Beaty Street
Davidson, North Carolina 28036
United States

Contact:

Patrick Rienks
Market Development Manager

Phone: (704) 896-4358
Fax: (704) 896-4372
E-mail: patrick_rienks@irco.com

Concentrator

Environmental C & C, Inc.

898 Route 146
Clifton Park, New York 12065
United States

Contact:

Hal Cowles

Phone: (518) 373-0005
Fax: (518) 373-0006
E-mail: hal@ecnc.com

Lean-Fuel Catalytic Turbine; VAM/Coal Co-Firing

CSIRO Australia

P.O. Box 883
Kenmore, Queensland, Australia
4069

Contact:

Dr. Michael Wendt

Phone: 61-7-3327 4679
Fax: 61-7-327 4455
E-mail: michael.wendt@csiro.au

Catalytic Microturbine

FlexEnergy

22922 Tiagua
Mission Viejo, CA 92692-1433
United States

Contact:

Edan Prabhu, President

Phone: (949) 380-4899
Fax: (949) 380-8407
E-mail: edanprabhu@cox.net

Carbureted Gas Turbine

Energy Developments Ltd. (EDL)

Australia Operations

Northhampton Dale Road
P.O. Box 83
Appin, New South Wales, Australia 2560

US Operations

7700 San Felipe Road
Suite 480
Houston, Texas 77063
United States

Contact:

Tom Chapman

E-mail: Tom.Chapman@edl.com.au

Australia
Phone: 61-2-4631-6200
Fax: 61-2-4631-1324

United States
Phone: (713) 781-5353
Fax: (713) 781-5303

Appendix E
CMOP Contact Information

For more information about the Coalbed Methane Outreach Program, contact:

Clark Talkington
Phone: 202-564-8969
Fax: 202-565-2134
E-mail: talkington.clark@epa.gov

Or visit the Program's web site at www.epa.gov/coalbed.

United States
Environmental Protection Agency
(6202-J)
Washington, DC 20460

www.epa.gov/coalbed